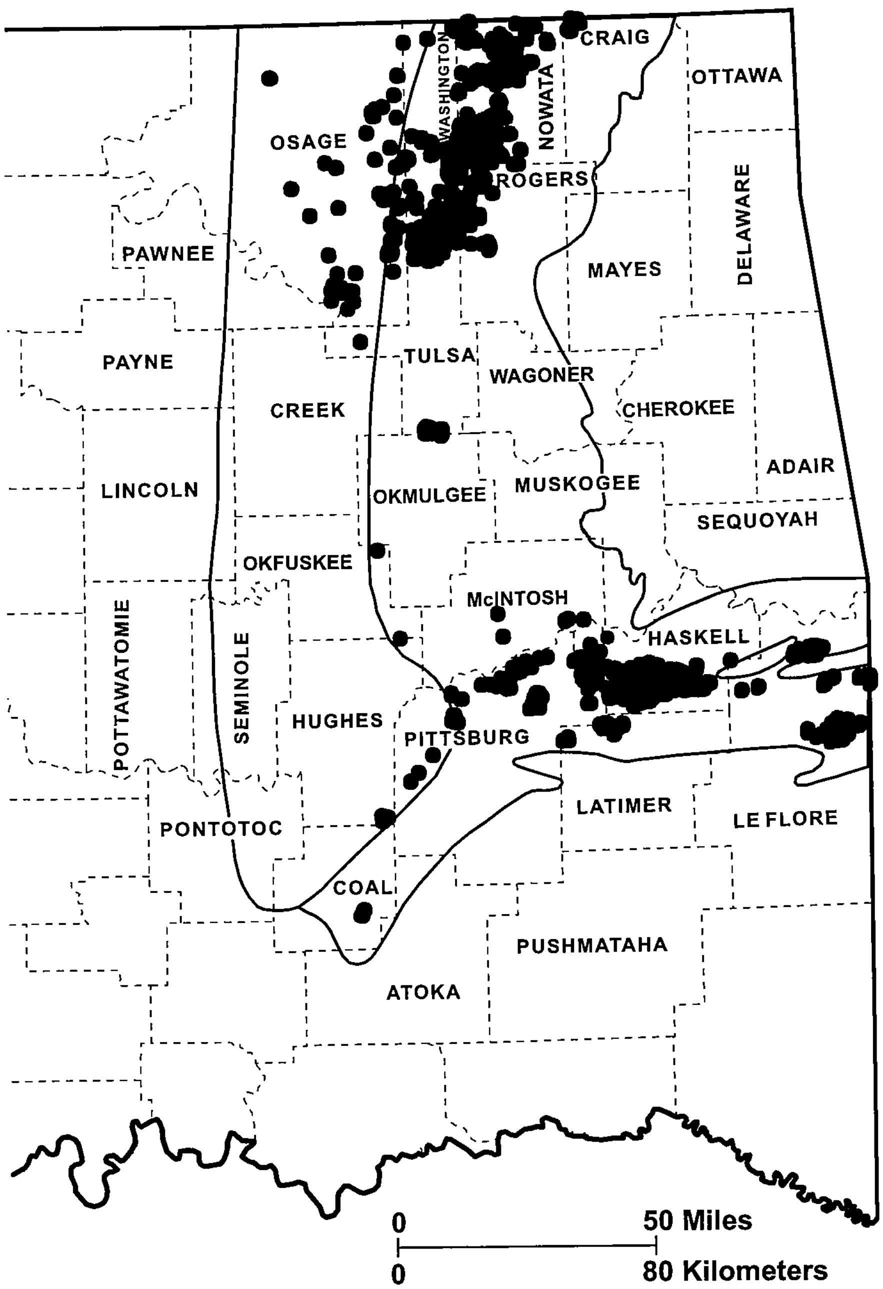
OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

OKLAHOMA COALBED-METHANE WORKSHOP 2001



OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

OKLAHOMA COALBED-METHANE WORKSHOP 2001

**Compiled by
Brian J. Cardott**

**Co-sponsored by
Oklahoma Geological Survey
and Petroleum Technology Transfer Council
(South-Midcontinent Region)**

Carl Albert State College
Poteau, Oklahoma
October 10, 2001

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Sisson, S.N., Hartshorne coalbed-methane economics in Oklahoma. (Presented at the Oklahoma Coalbed-Methane Workshop in Oklahoma City on March 29, 2001)

Cardott, B.J., Coalbed methane (selected references for Oklahoma)

Cardott, B.J., Bibliography of Oklahoma coal.

OKLAHOMA GEOLOGICAL SURVEY
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1

Introduction to coal as gas source rock and reservoir

Brian J. Cardott
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Norman, OK

Cardott, B.J., 2001, Introduction to coal as gas source rock and reservoir, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 1-27.

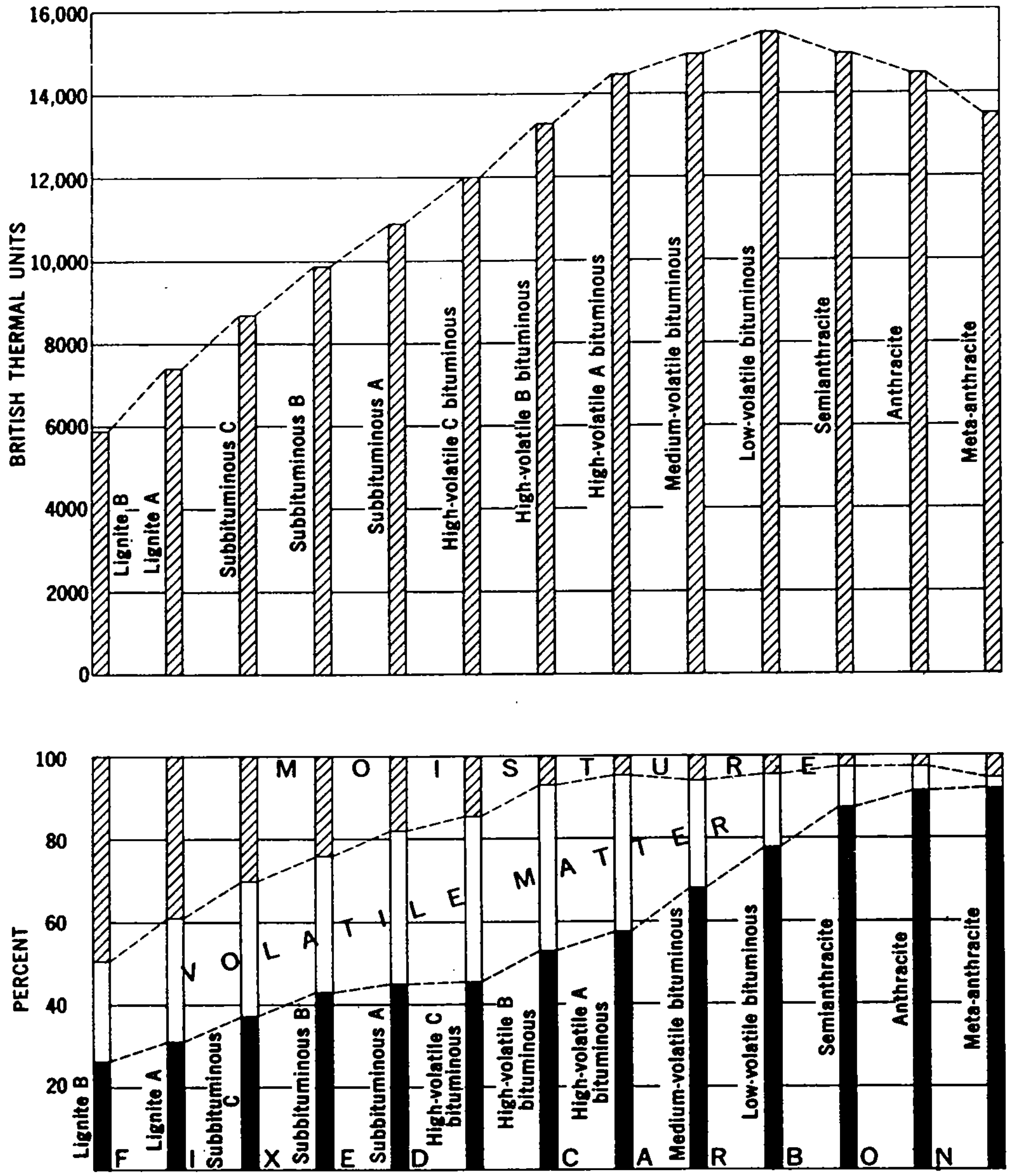
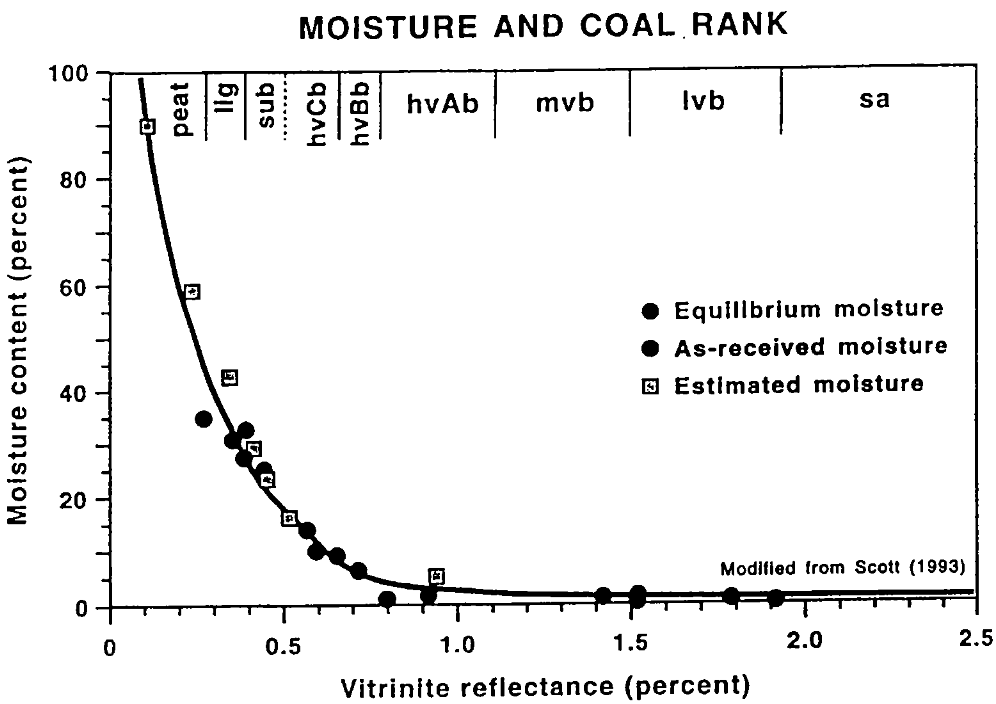


FIGURE 3.—Comparison on moist, mineral-matter-free basis of heat values and proximate analyses of coal of different ranks.

From Averitt, Paul, 1975, Coal resources of the United States, January 1, 1974: USGS Bulletin 1412, p. 17.



From Scott, A.R., 2000, Hydrogeologic controls affecting gas content variability in coal beds, in Coalbed methane: from prospect to production: Short course for Opportunities in Alaska coalbed methane workshop.

MACERAL GROUP	ORIGIN	REFLECTANCE
VITRINITE	Cell wall material or woody tissue of plants.	Intermediate
LIPTINITE (EXINITE)	Waxy and resinous parts of plants (spores, cuticles, wound resin)	Lowest
INERTINITE	Plant material strongly altered and degraded in peat stage of coal formation.	Highest

Adapted from Crelling, J.C., and R.R. Dutcher, 1980, Principles and applications of coal petrology: SEPM Short Course No. 8, 127 p.

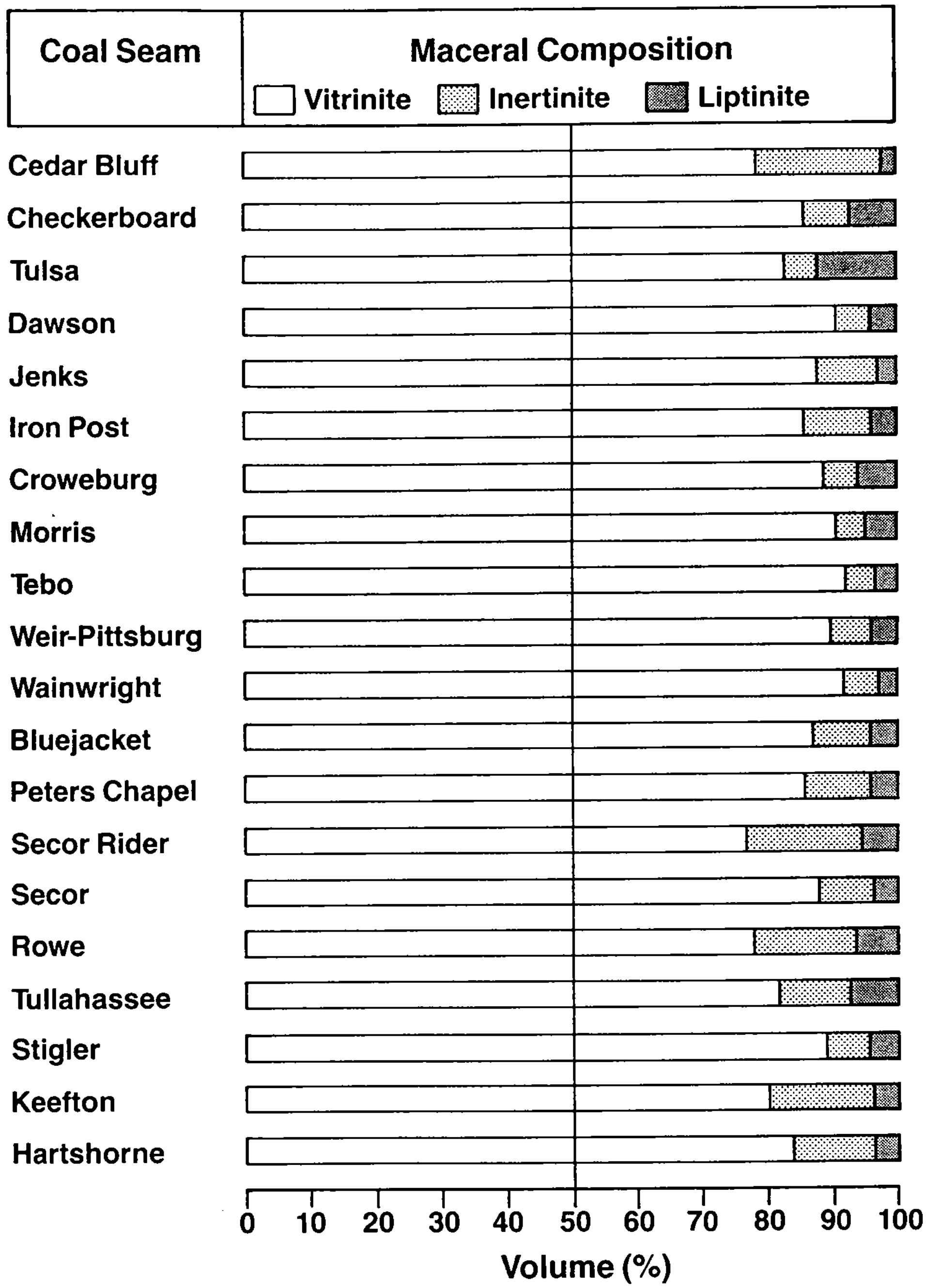
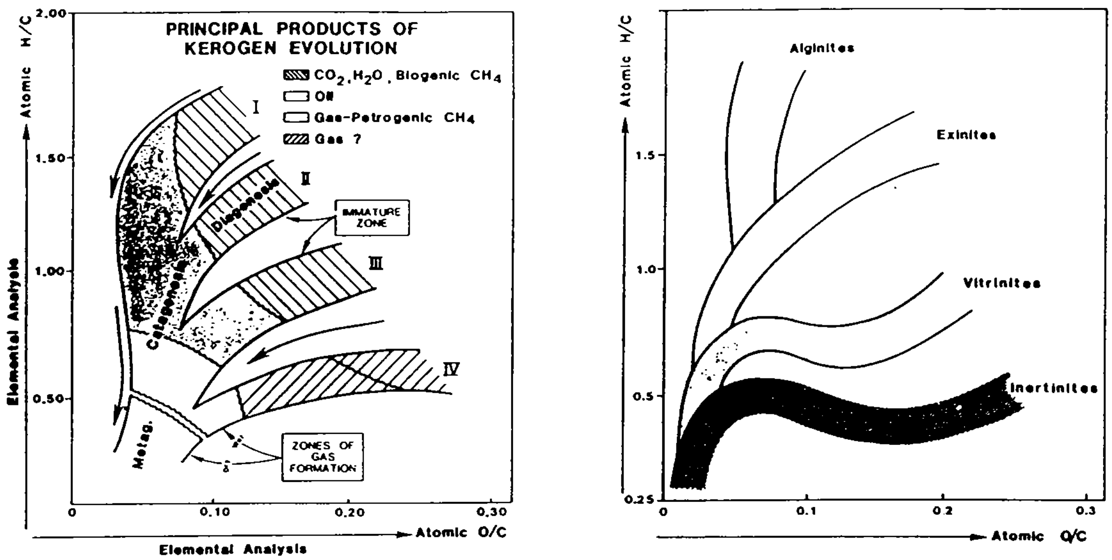


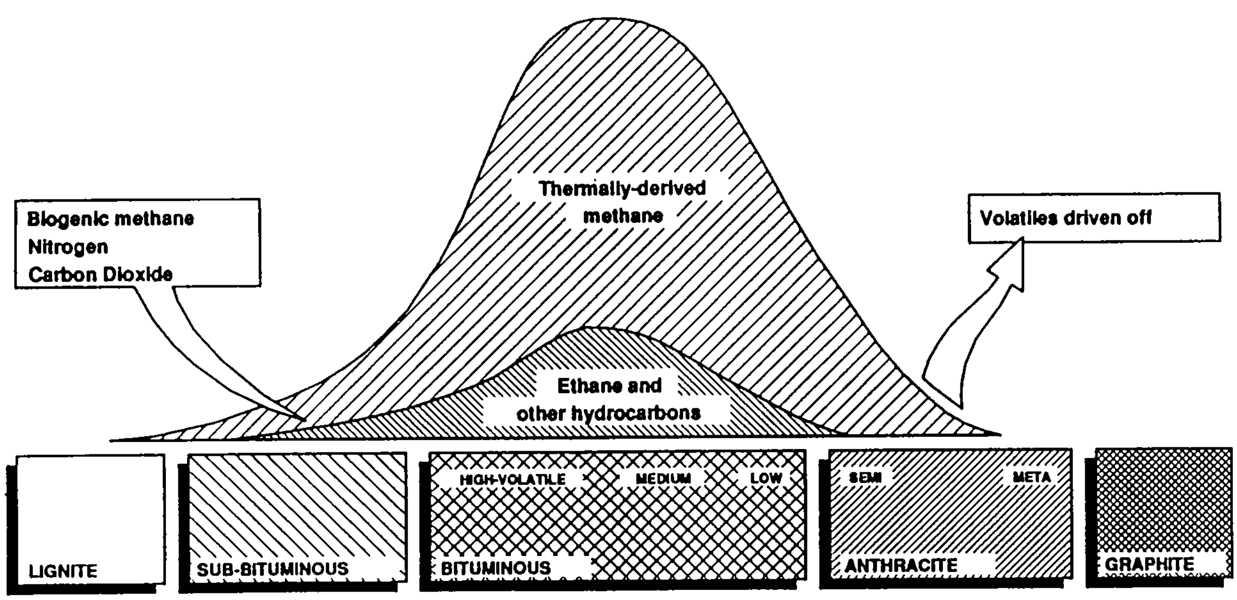
Figure 3. Maceral composition of selected high-volatile bituminous Oklahoma coals, expressed as percentage by volume on a mineral-free basis.

From Cardott, B.J., 1989, A petrographic survey of high-volatile bituminous Oklahoma coal beds: Oklahoma Geology Notes, v. 49, p. 119.



From Geochem Laboratories, 1980, Source rock evaluation reference manual: Houston, Texas, Geochem Laboratories, Inc., p. B-9.

GAS GENERATION IN COAL



From Boyer, C.M., II, 1989, The coalbed methane resource and the mechanisms of gas production: GRI Topical Report, GRI-89-0266, p. 46.

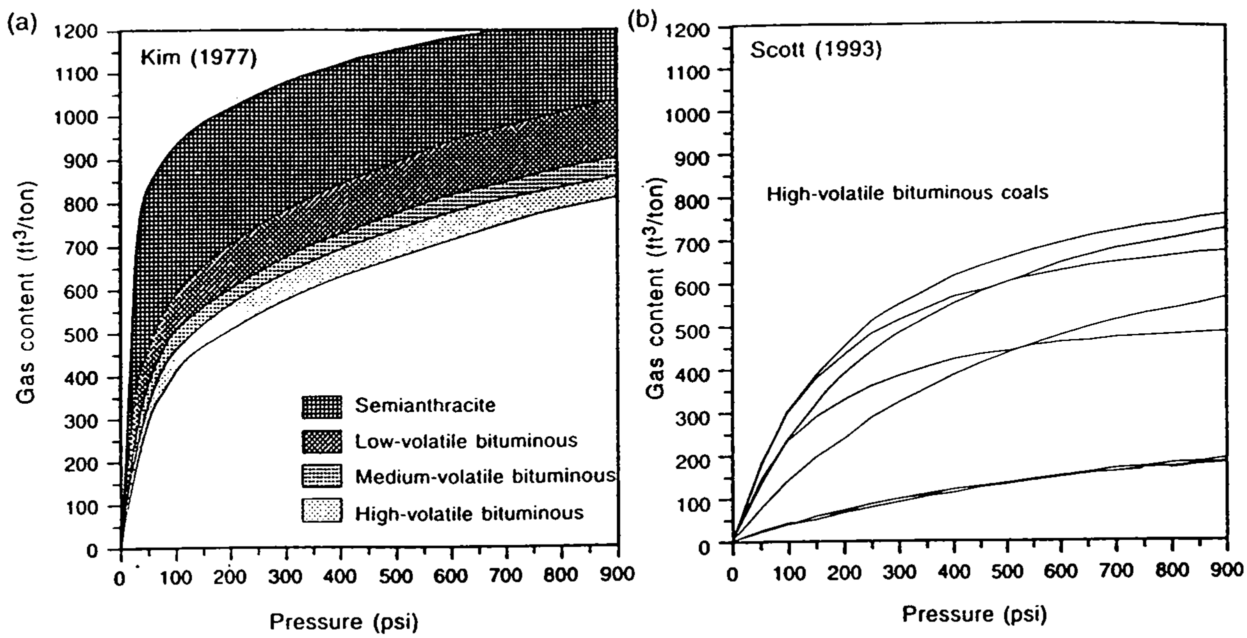
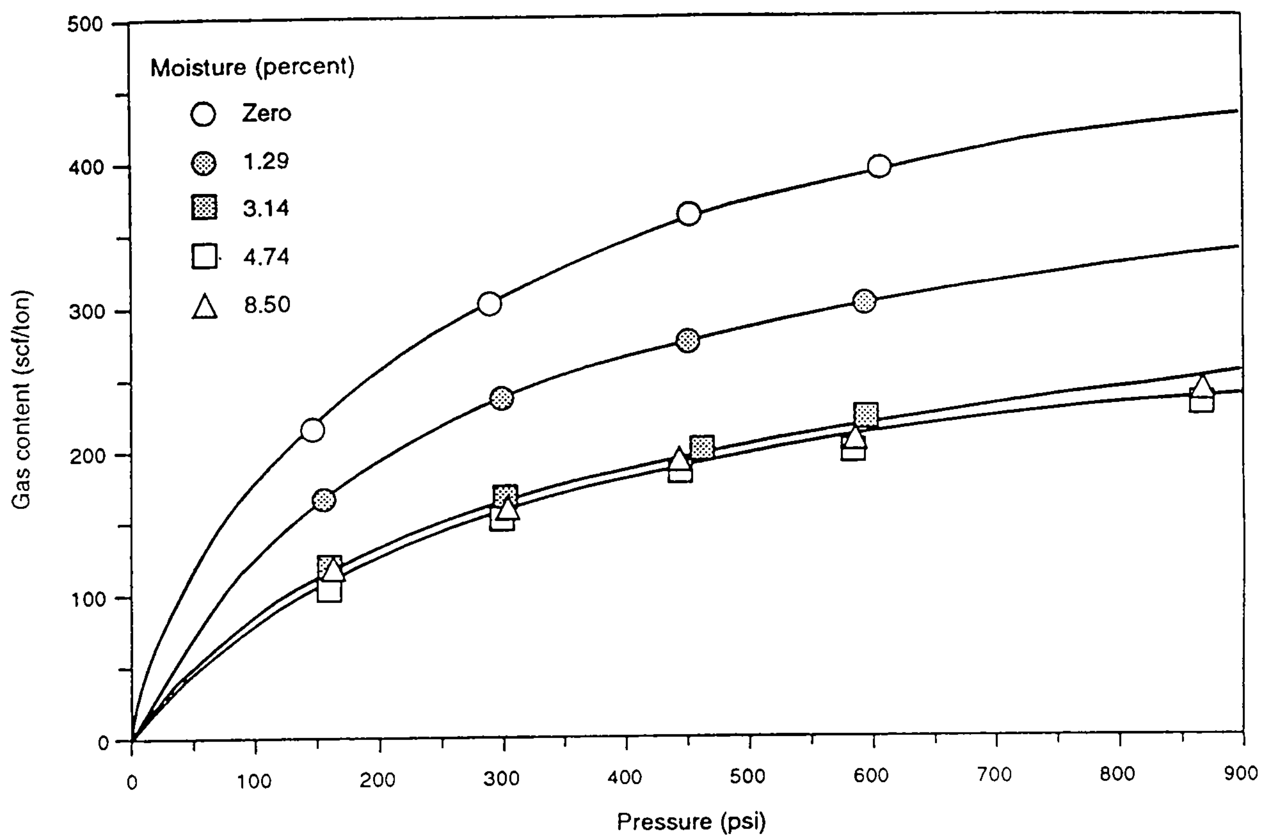


Figure 4—Rank dependence of gas content with increasing pressure. (a) Gas content is assumed to progressively increase with increasing rank (Kim, 1977). (b) However, many factors affect gas content in coal beds, and similarly ranked coals commonly exhibit a wide range of gas contents (Scott, 1993a).

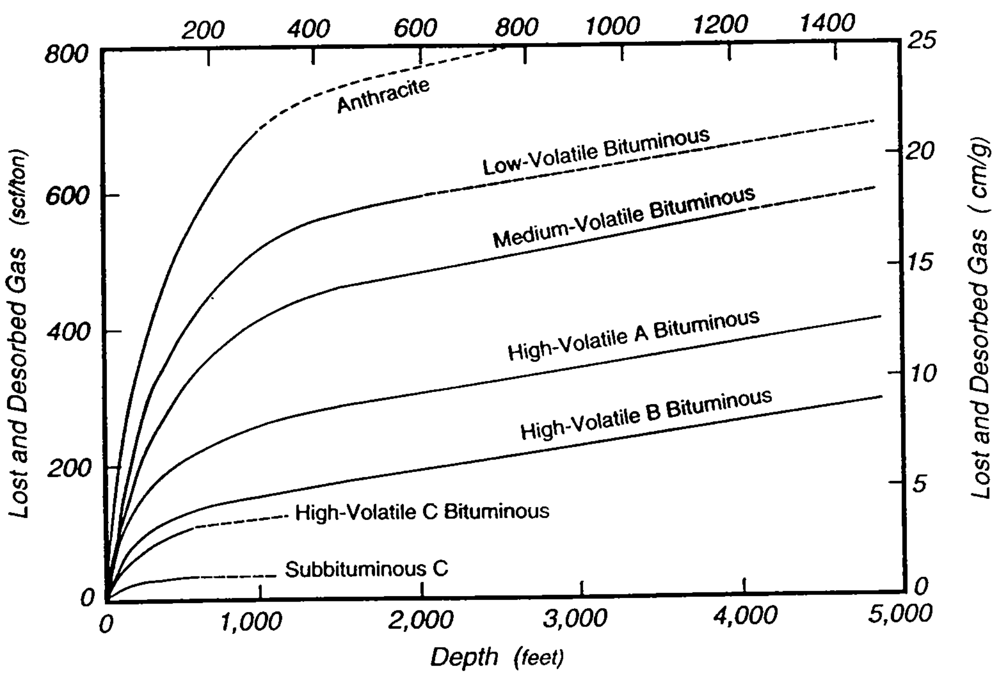
From Scott, A.R., N. Zhou, and J.R. Levine, 1995, A modified approach to estimating coal and coal gas resources: example from the Sand Wash basin, Colorado: AAPG Bulletin, v. 79, p. 1325.



Variation of sorption capacity with moisture content. Gas sorption capacity decreases significantly with increasing moisture content until an upper limit of moisture content is reached. At this point, additional moisture has no effect on sorption capacity. From Joubert, J.I., C.T. Grein, and D. Bienstock, 1974, Effect of moisture on the methane capacity of American coals: Fuel, v. 53, p. 186-191.

Figure 2-9

Estimated Maximum Producible Methane Content by Depth and Rank *(Adapted from Eddy, 1982)*



From Saulsberry, J.L., P.S. Schafer, and R.A. Schraufnagel, eds., 1996, A guide to coalbed methane reservoir engineering: Chicago, Gas Research Institute, page 2.9.

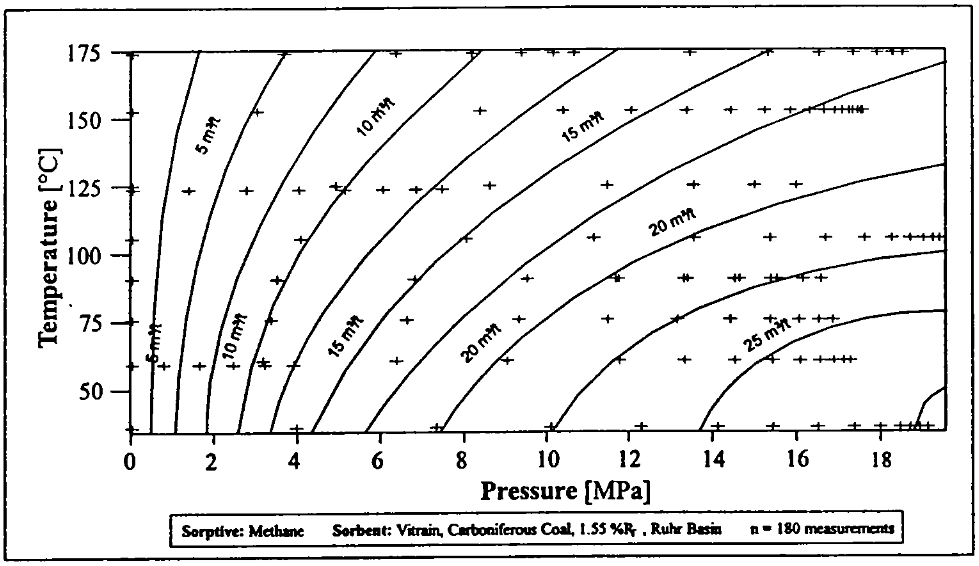
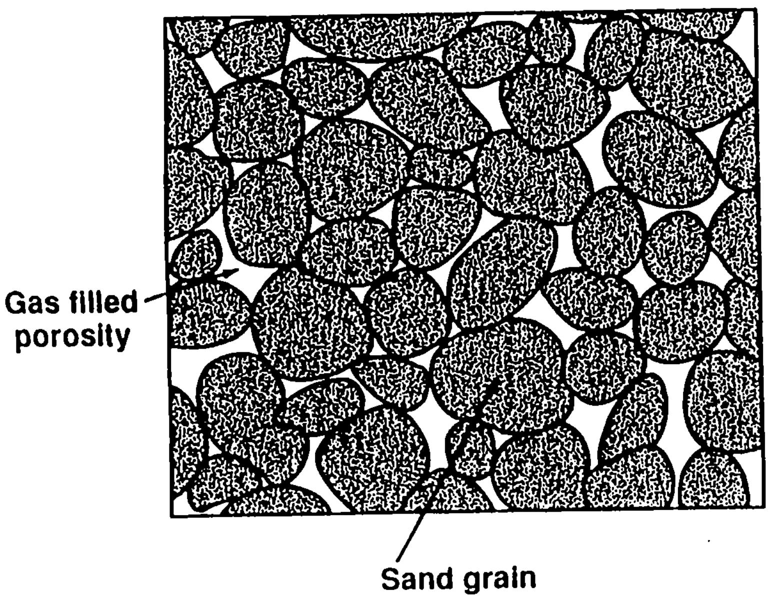


Figure 1: Pressure and temperature dependence of the adsorption capacity of organic matter

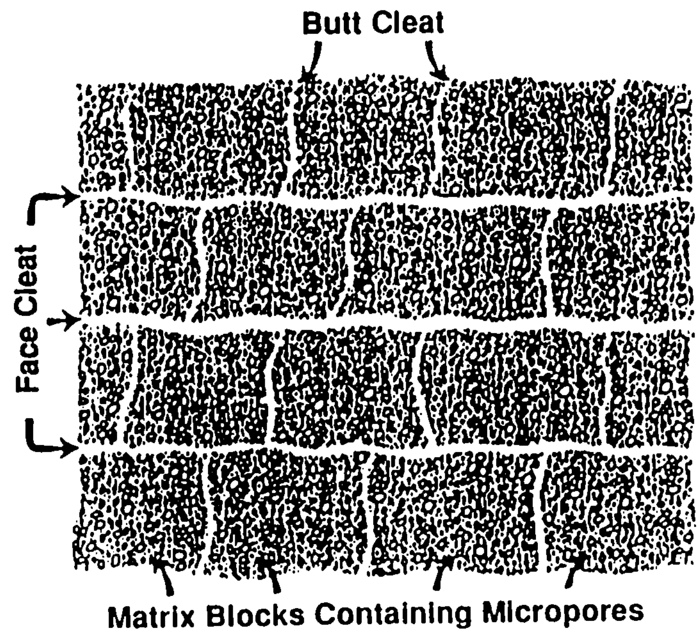
From Gaschnitz, R., B.M. Kroos, and R. Littke, 1997, Coalbed methane: adsorptive gas storage capacity of coal seams in the Upper Carboniferous of the Ruhr basin, Germany (extended abstract): TSOP Abstracts and Program, v. 14, p. 44.

STRUCTURAL COMPARISON

Conventional Gas Sand



Coalbed



From Boyer, C.M., II, 1989, The coalbed methane resource and the mechanisms of gas production: GRI Topical Report, GRI-89-0266, p. 61.

CLEAT ORIGIN AND IMPORTANCE

- **Miners' term for natural fractures in coal. Coal breaks along cleat planes.**

- **Control the directional permeability of coal. Important for planning CBM well placement and spacing.**

- **Result of dehydration, devolatilization, tectonic stress during coalification, and unloading of overburden during uplift and erosion.**

References on cleat:

Close, J.C., 1993, Natural fractures in coal, in B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 119-132.

Laubach, S.E., R.A. Marrett, J.E. Olson, and A.R. Scott, 1998, Characteristics and origins of coal cleat: a review, in R.M. Flores, ed., Coalbed methane: from coal-mine outbursts to a gas resource: International Journal of Coal Geology, v. 35, p. 175-207.

Law, B.E., 1993, The relationship between coal rank and cleat spacing: implications for the prediction of permeability in coal: Proceedings of the 1993 International CBM Symposium, paper 9341, p. 435-442.

McCulloch, C.M., M. Deul, and P.W. Jeran, 1974, Cleat in bituminous coalbeds: U.S. Bureau of Mines Report of Investigations 7910, 25 p.

Su, X., Y. Feng, J. Chen, and J. Pan, 2001, The characteristics and origins of cleat in coal from western North China: International Journal of Coal Geology, v. 47, p. 51-62.

Ting, F.T.C., 1977, Origin and spacing of cleats in coal beds: Journal of Pressure Vessel Technology, v. 99, p. 624-626.

CLEAT ORIENTATION

- Two orthogonal sets, perpendicular to bedding. Complicated by local disturbances such as faults and folds.

  Face Cleat—dominant, well developed, extend across bedding planes of the coal. Extension fractures formed parallel to maximum compressive stress.

  Butt Cleat—secondary, discontinuous, terminate against face cleat. Strain-release fractures formed parallel to fold axes.

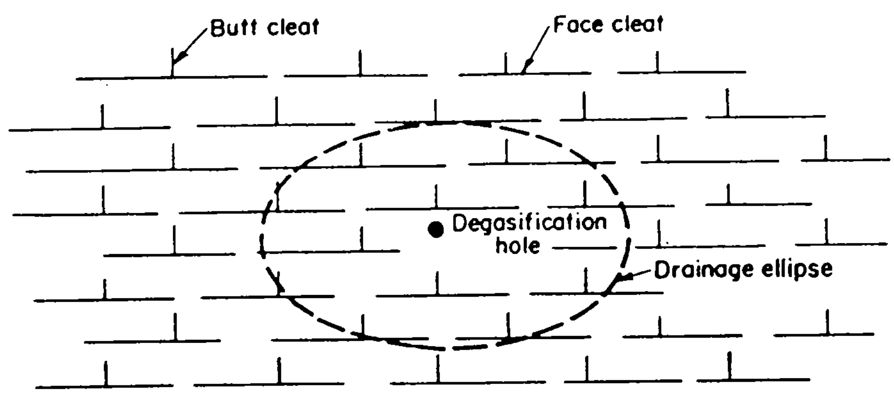
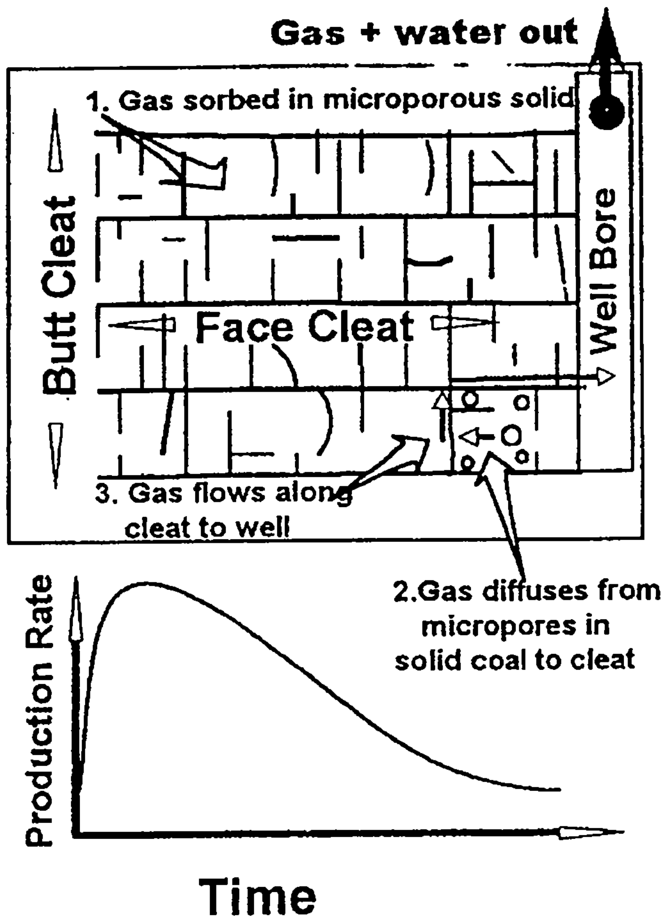


Figure 4-1.—Plan view of directional permeability due to cleat orientation,

From Diamond, W.P., C.H. Elder, and P.W. Jeran, 1988, Influence of geology on methane emission from coal, in M. Deul and A.G. Kim, Methane control research: summary of results, 1964-80: U.S. Bureau of Mines Bulletin 687, p. 26.

Coal Bed Gas Production



From Barker, C.E., A.R. Scott, and R.A. Downey, 2000, Coalbed methane: from prospect to production: Opportunities in Alaska coalbed methane workshop, p. 7.

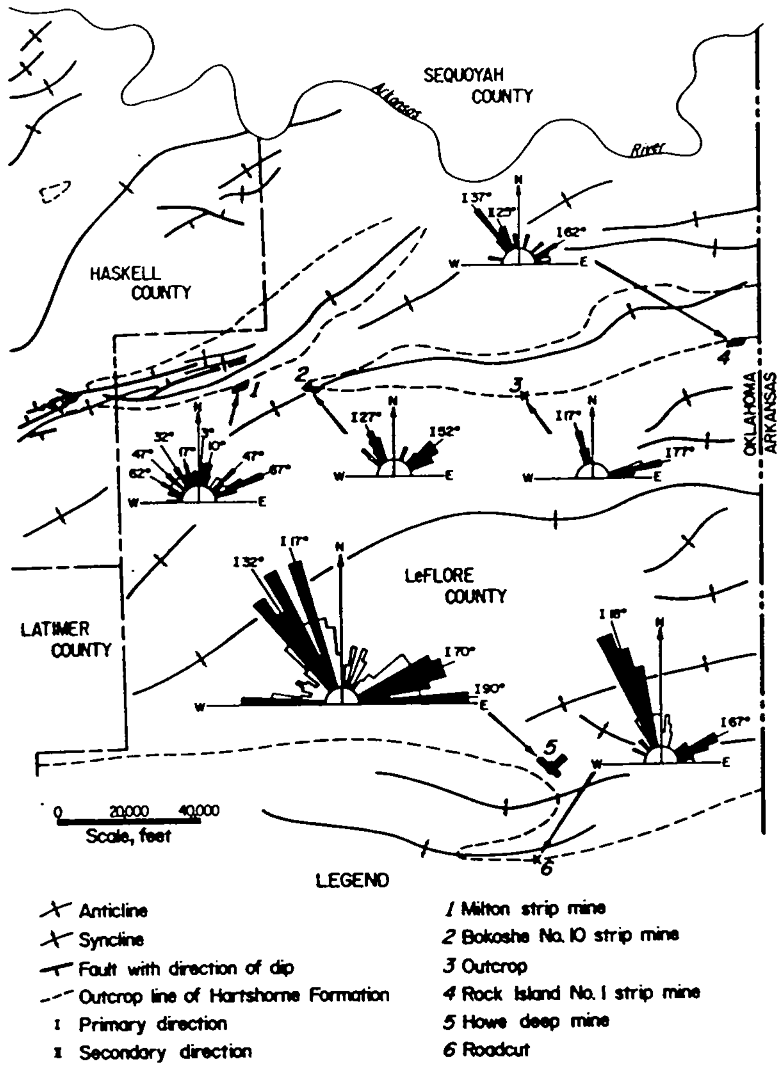


FIGURE 9. - Coal cleat orientations of the Hartshorne coalbed in Le Flore County.

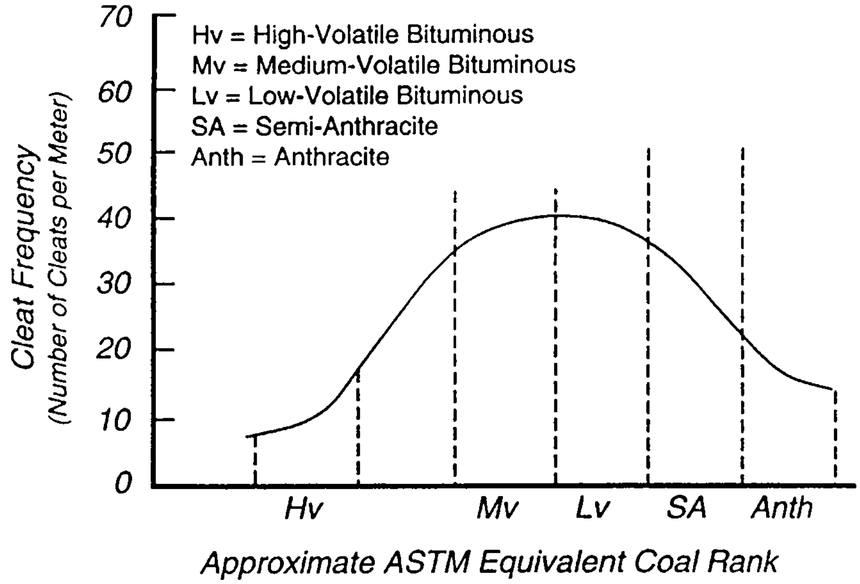
From Iannacchione, A.T., and D.G. Puglio, 1979, Methane content and geology of the Hartshorne coalbed in Haskell and Le Flore Counties, Oklahoma: U.S. Bureau of Mines Report of Investigations 8407, p. 9.

CLEAT SPACING

- Related to rank, bed thickness, and composition. Coal with well-developed cleat is brittle.

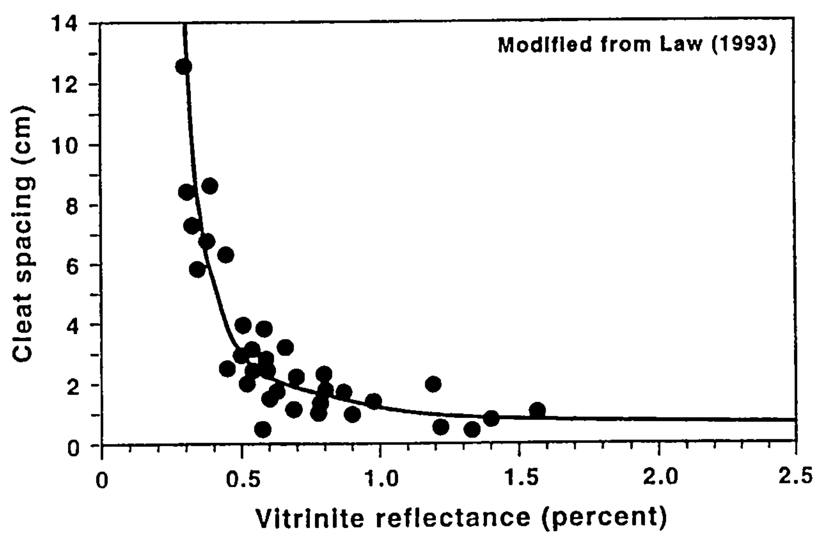
  Rank—more frequent with increasing rank from lignite to low-volatile bituminous.
  Subbituminous: 2–15 cm
  High-volatile bituminous: 0.3–2 cm
  Medium- to Low-volatile bituminous: <1 cm.

Cross-plot of Coal Rank and Cleat Frequency
(Adapted from Ammosov and Eremin, 1960)



From Saulsberry, J.L., P.S. Schafer, and R.A. Schraufnagel, eds., 1996, A guide to coalbed methane reservoir engineering: Chicago, Gas Research Institute, page 2.7.

CLEAT SPACING AND COAL RANK



Modified from Law, B.E., 1993, The relationship between coal rank and cleat spacing: implications for the prediction of permeability in coal: Proceedings of the 1993 International CBM Symposium, paper 9341, p. 435-442.

CLEAT SPACING (continued)

Bed Thickness—more frequent in thinner coals.

Composition—

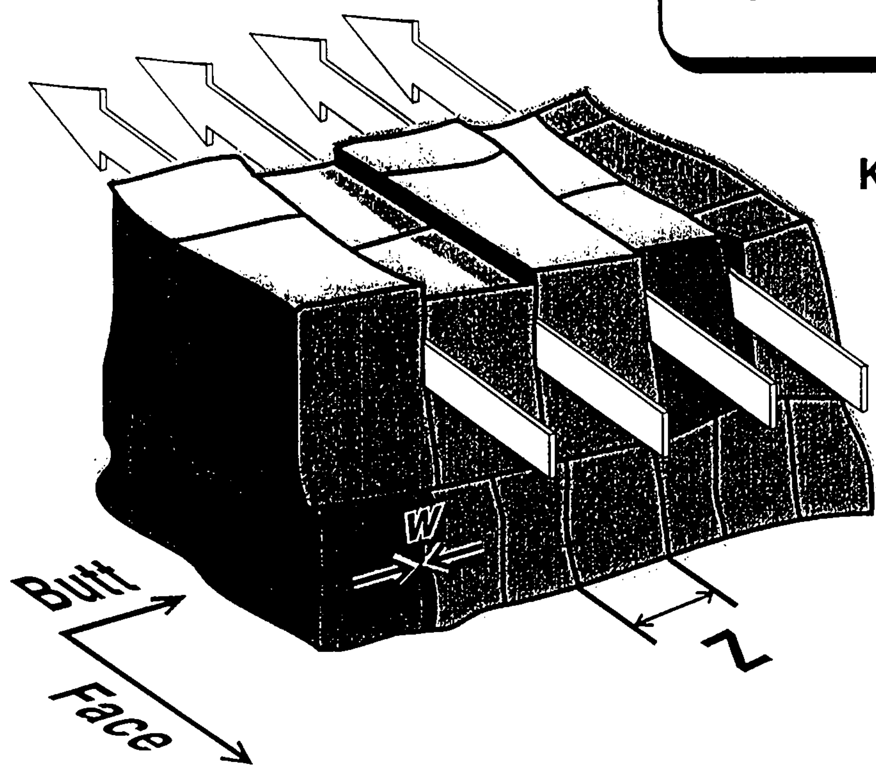
Coal type: more frequent in banded than nonbanded coals.

Coal lithotype: more frequent in bright, vitrinite-rich lithotypes than in dull, inertinite- and liptinite-rich lithotypes.

Coal grade: more frequent in low-ash (mineral matter) coals.

FRACTURE FLOW IN COAL BEDS

$$K_S = \frac{w^3}{Z} (84.4 \times 10^5)$$



K_S = permeability (darcy)

w = cleat aperture (cm)

Z = cleat spacing (cm)

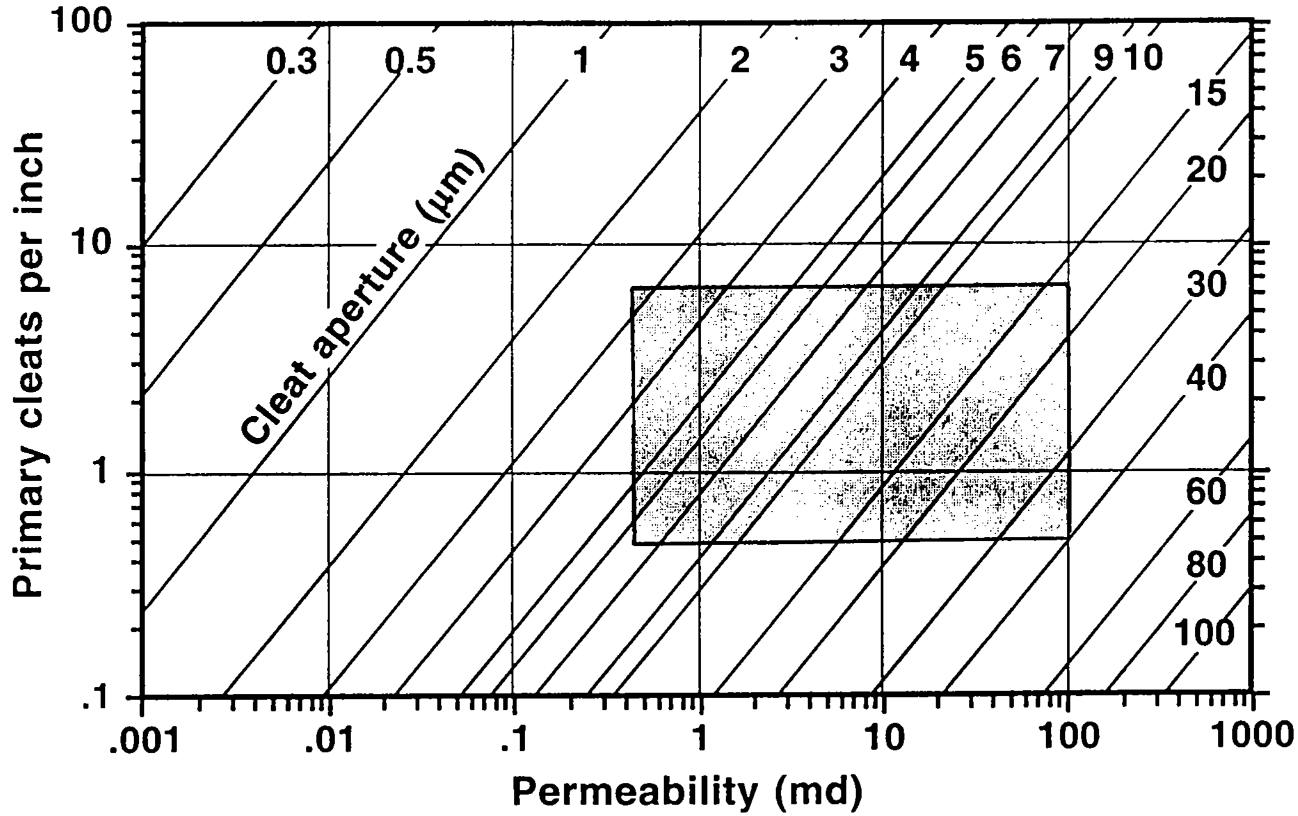
* Lucia (1983)

GRI/BEG

44c

From Scott, A.R., 2000, Application of burial history and coalification to coalbed methane producibility, in Coalbed methane: from prospect to production: Short course for Opportunities in Alaska coalbed methane workshop.

CLEAT APERTURES



Modified from Scott (1995)

GRI/BEG

QAa9042c

CLEAT MINERALIZATION

- **Secondary mineralization of cleat will lower porosity and permeability of coal:**
  Clay (kaolinite)
  Calcite
  Gypsum
  Quartz
  Sulfide (e.g., pyrite)

References on cleat mineralization:

Close, J.C., 1993, Natural fractures in coal, in B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 119-132.

Gamson, P., B. Beamish, and D. Johnson, 1996, Coal microstructure and secondary mineralization: their effect on methane recovery, in R. Gayer and I. Harris, eds., Coalbed methane and coal geology: London, Geological Society Special Publication 109, p. 165-179.

Laubach, S.E., R.A. Marrett, J.E. Olson, and A.R. Scott, 1998, Characteristics and origins of coal cleat: a review, in R.M. Flores, ed., Coalbed methane: from coal-mine outbursts to a gas resource: International Journal of Coal Geology, v. 35, p. 175-207.

Spears, D.A., and S.A. Caswell, 1986, Mineral matter in coals: cleat minerals and their origin in some coals from the English Midlands: International Journal of Coal Geology, v. 6, p. 107-125.

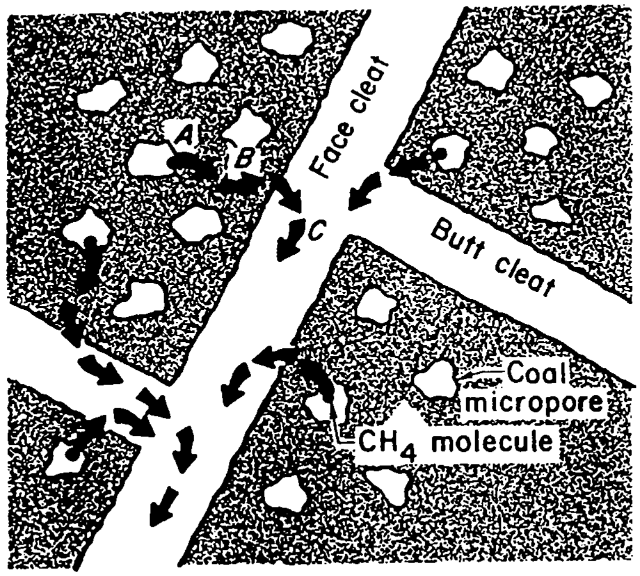
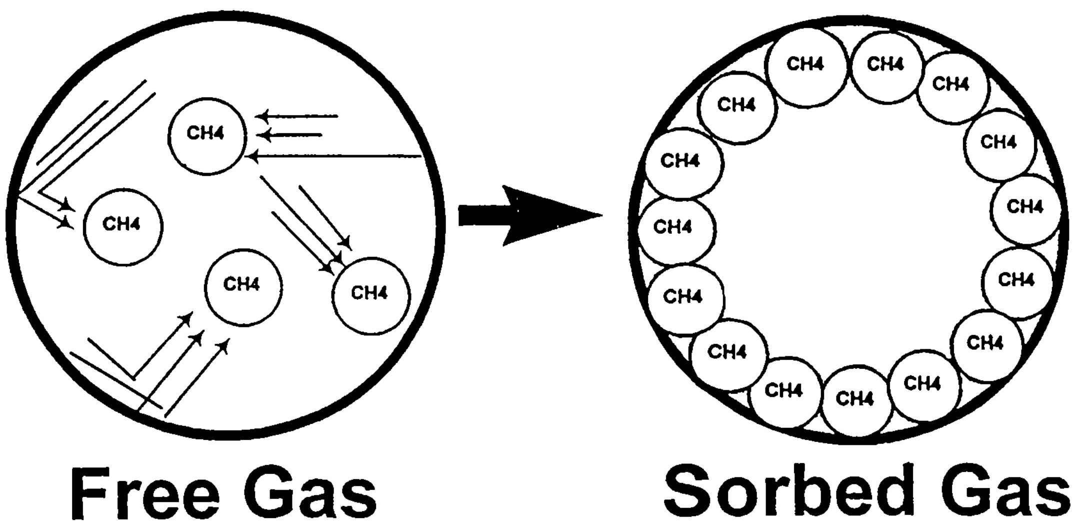


Figure 6. Schematic plan view of (A) desorption of methane from coal micropore, (B) diffusion through coal matrix, and (C) darcy flow through cleat.

From Diamond, W.P., 1993, Methane control for underground coal mines, in B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 242.



From Barker, C.E., A.R. Scott, and R.A. Downey, 2000, Coalbed methane: from prospect to production: Opportunities in Alaska coalbed methane workshop, p. 7.

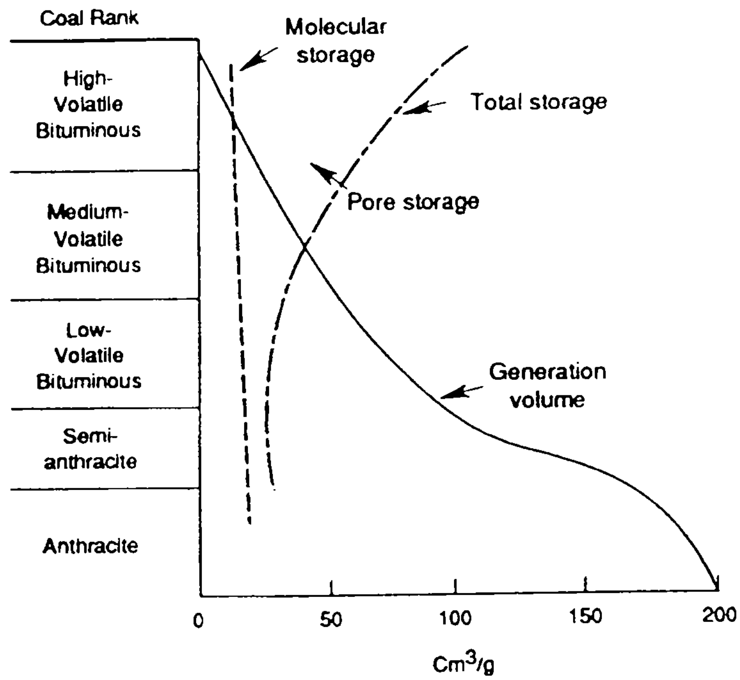
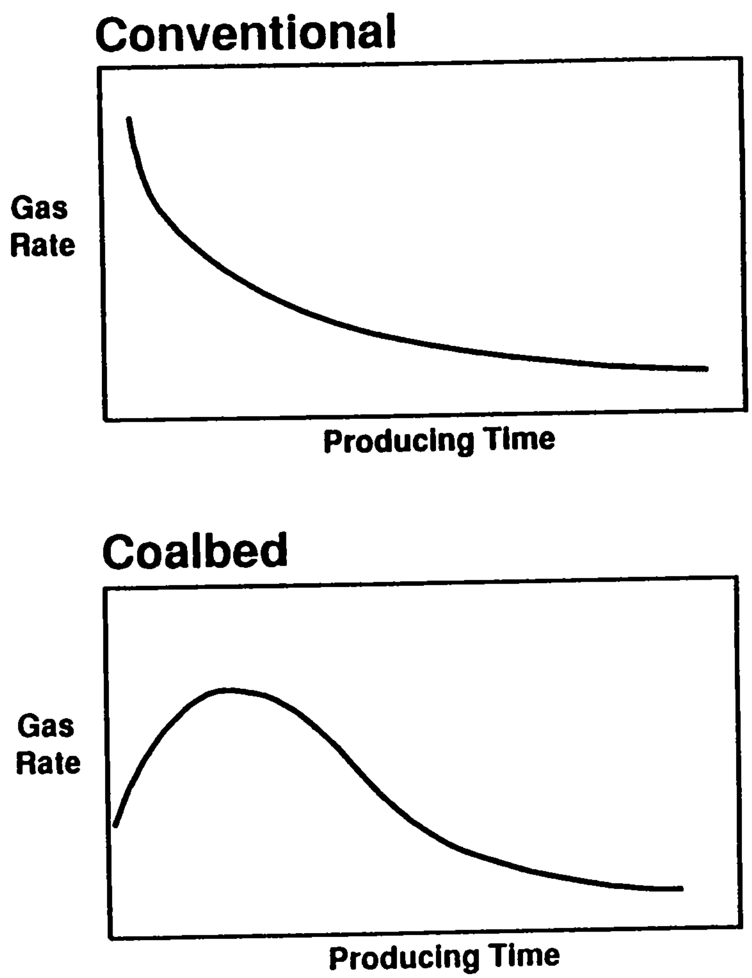


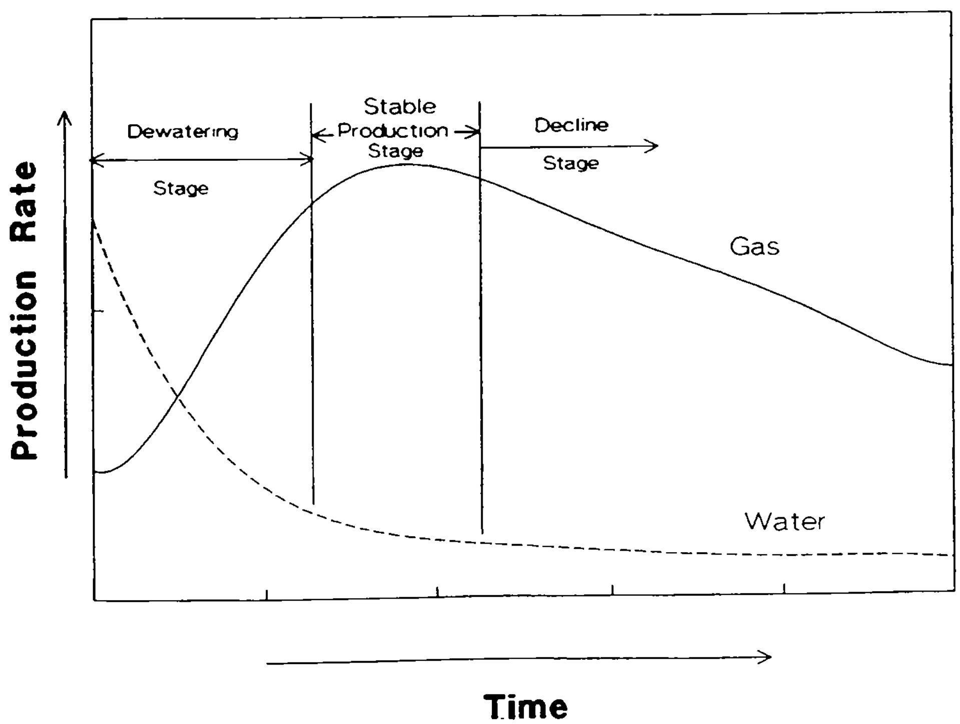
Figure 5. Plot showing volumes of methane generated and stored per gram of coal with increasing rank. Modified from Meissner (1984) and P.D. Jenden (personal communication, 1992).

From Rice, D.D., 1993, Composition and origins of coalbed gas, in B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 162.

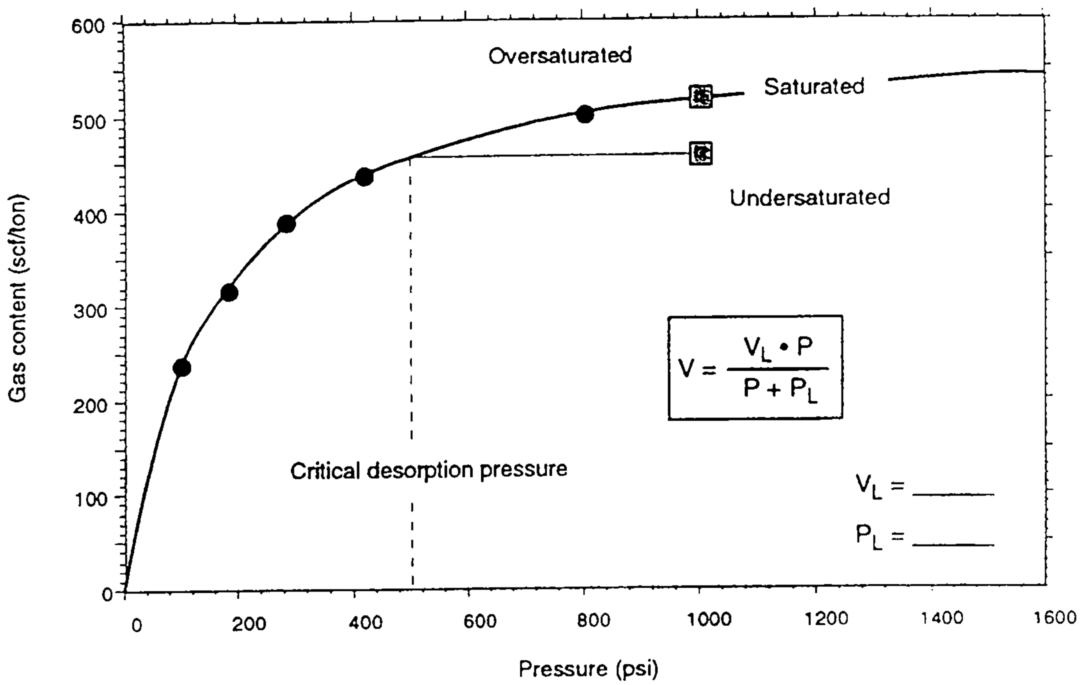


From Boyer, C.M., II, 1989, The coalbed methane resource and the mechanisms of gas production: GRI Topical Report, GRI-89-0266, p. 64.

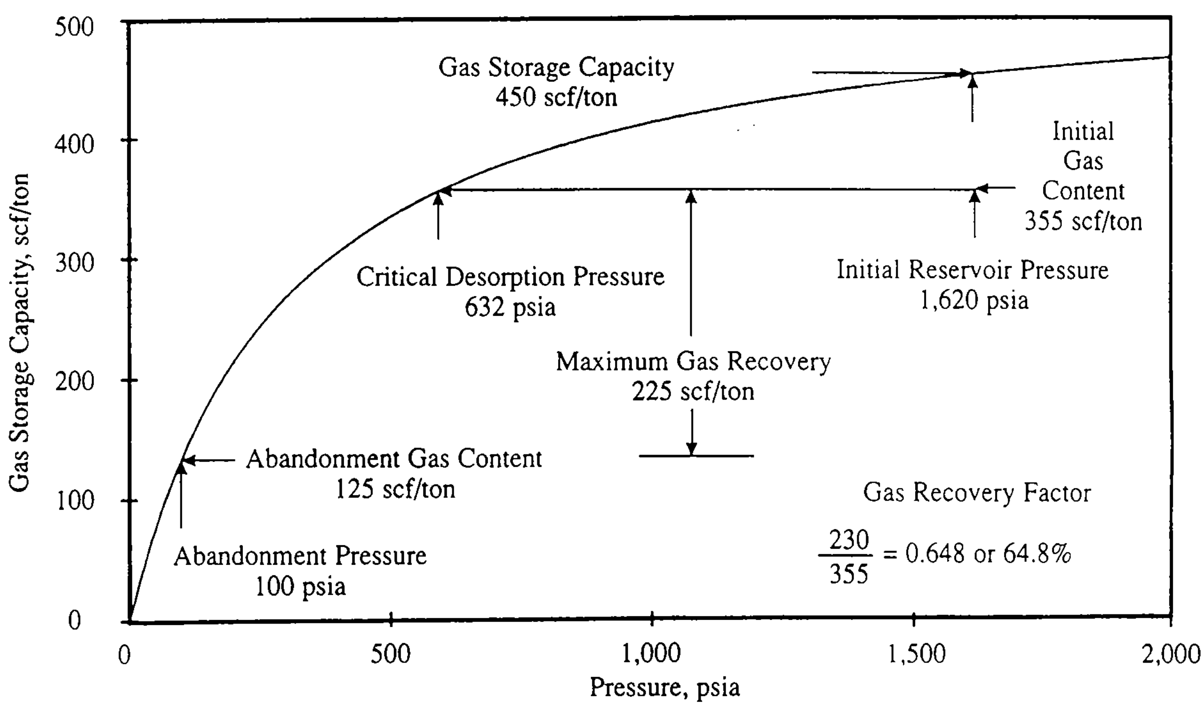
Figure 2. A typical production profile for a coalbed methane well.



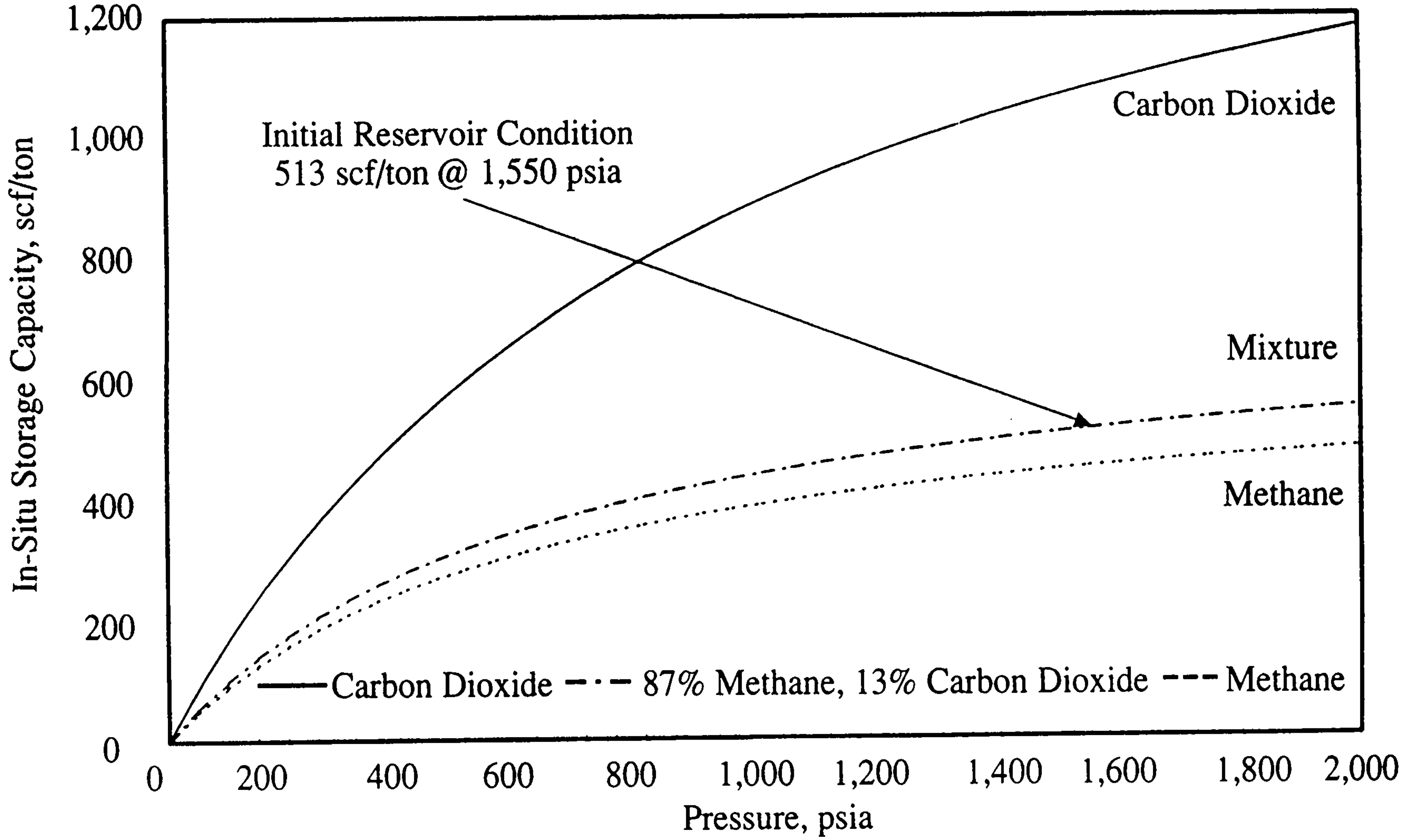
From Schraufnagel, R.A., 1993, Coalbed methane production, in B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 343.



From Scott, A.R., 1995, Factors affecting gas-content distribution in coal beds, in Geology and hydrology of coalbed methane producibility in the United States: analogs for the world: Gas Research Institute, Intergas '95 short course, p. 232.



From Mavor, M., and C.R. Nelson, 1997, Coalbed reservoir gas-in-place analysis: Chicago, Gas Research Institute, GRI-97/0263, p. 6.2.



From Mavor, M., and C.R. Nelson, 1997, Coalbed reservoir gas-in-place analysis: Chicago, Gas Research Institute, GRI-97/0263, p. 6.4.

$GIP = (h \times A) \times \rho \times GC$

GIP	Gas-in-place (scf)
h	Coal thickness (ft)
A	Drainage area (acres)
ρ	Coal bulk density (tons/acre-foot) [@ 1,800]
GC	Gas content (scf/ton)

$GIP = 1{,}359.7\ (h \times A) \times \rho \times GC$

GIP	Gas-in-place (scf)
h	Coal thickness (ft)
A	Drainage area (acres)
ρ	Ash-free coal density (g/cm^3) (lowest value on density log)
GC	Ash-free gas content (scf/ton)

[1,359.7 converts g/cm^3 to tons/acre-foot]

[from Mavor, M., and C.R. Nelson, 1997, Coalbed reservoir gas-in-place analysis: Chicago, Gas Research Institute, GRI-97/0263]

OKLAHOMA GEOLOGICAL SURVEY
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2

A coalbed methane exploration model: application to the Cherokee, Forest City, and Arkoma basins

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Scott, A.R., 2001, A coalbed methane exploration model: application to the Cherokee, Forest City, and Arkoma basins, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 28-43.

A Coalbed Methane Exploration Model: Application to the Cherokee, Forest City, and Arkoma

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ABSTRACT

Coalbed methane has recently developed into one of the most active gas plays of the United States. Geologic and hydrologic comparisons of coal basins worldwide, indicate that depositional systems and coal distribution, coal rank, gas content, permeability, hydrodynamics, and tectonic/structural setting are critical controls on coalbed methane producibility. A dynamic interplay among these controls determines high coalbed methane productivity. This paper reviews a basin-scale exploration model for the prolific and marginal gas production in two basins that can be applied to evaluation of coalbed methane potential in coal basins worldwide. High productivity is governed by (1) thick, laterally continuous coals of high thermal maturity; (2) moderate to high permeability; (3) basinward flow of ground water through coals of high rank orthogonally toward no-flow boundaries (permeability barriers, regional structural hingelines, fault systems, facies changes, and/or discharge areas); (4) generation of secondary biogenic gases; and (5) conventional trapping of migrated thermogenic and secondary biogenic gases at permeability barriers to provide additional gas beyond that generated during coalification. Understanding the dynamic interaction among geologic and hydrologic factors is important for delineating areas within basins that potentially have higher coalbed methane productivity. Correct application of a coalbed methane exploration model can delineate areas of potentially higher coalbed methane, provide more accurate resource assessment, and determine which areas have significantly lower coalbed methane potential.

INTRODUCTION

Coalbed methane is an important part of the natural gas supply for the United States and now represents more than 7 percent of total gas production and 7 percent of dry gas proved reserves (Energy Information Association; 2000). Although initial coal gas exploration and development was performed initially by major oil companies and larger independents, smaller operators have played a progressively more important role in developing this natural resource. Coal gas resources for the contiguous United States are estimated to be more than 755 Tcf (21.38 Tm^3) and more than 80 percent is located in the western United States (Figure 1). Coalbed methane resources in Alaska probably exceed 1,037 Tcf (29.36 Tm^3) (Clough and others, 2001).

Annual coal gas production has increased from less than 10 Bcf in 1986 to more than 1,249 Bcf (35.36 Bm^3) in 1996 (Figure 2). Although over 80 percent of current coal gas production is derived from the San Juan Basin, coal gas production from other western basins continues to increase, particularly from the Powder River Basin. Coal gas proved reserves remained relatively constant, increasing slightly over the past 4 years, and are current;ly estimated to be approximately 13.23 Tcf (375 Bm^3)(Energy Information Association; 2000). The increase in proved coal gas reserves despite the significant increase in production is attributed to the efforts of smaller operators and independents in finding new reserves. Coal gas production and reserves are expected to increase as exploration continues in unexplored areas and as secondary recovery techniques using nitrogen or carbon dioxide are employed.

The traditional view of production from coalbed methane reservoirs is inadequate to explain the contrasts in methane producibility of coal basins. This paper presents our explanation of the geological and hydrological controls that are critical to coalbed methane producibility. In the traditional view, coal gases are generated in situ during coalification and are stored primarily in micropores on the coal matrix's large internal surface area by sorption (Thimons and Kissell, 1973). The sorption process is pressure dependent, and the gas is held in coal micropores by the pressure of water in the coal's natural fracture network, or cleat system (Kolesar and others, 1990). Gas production is achieved by reducing the reservoir pressure through dewatering and thus liberating the gases from the coal matrix into the cleat system for flow to the well bore. The traditional view is oversimplified because it fails to recognize the need for additional sources of gas beyond that generated initially during coalification to achieve high gas content following basinal uplift and cooling. Migrated conventionally and

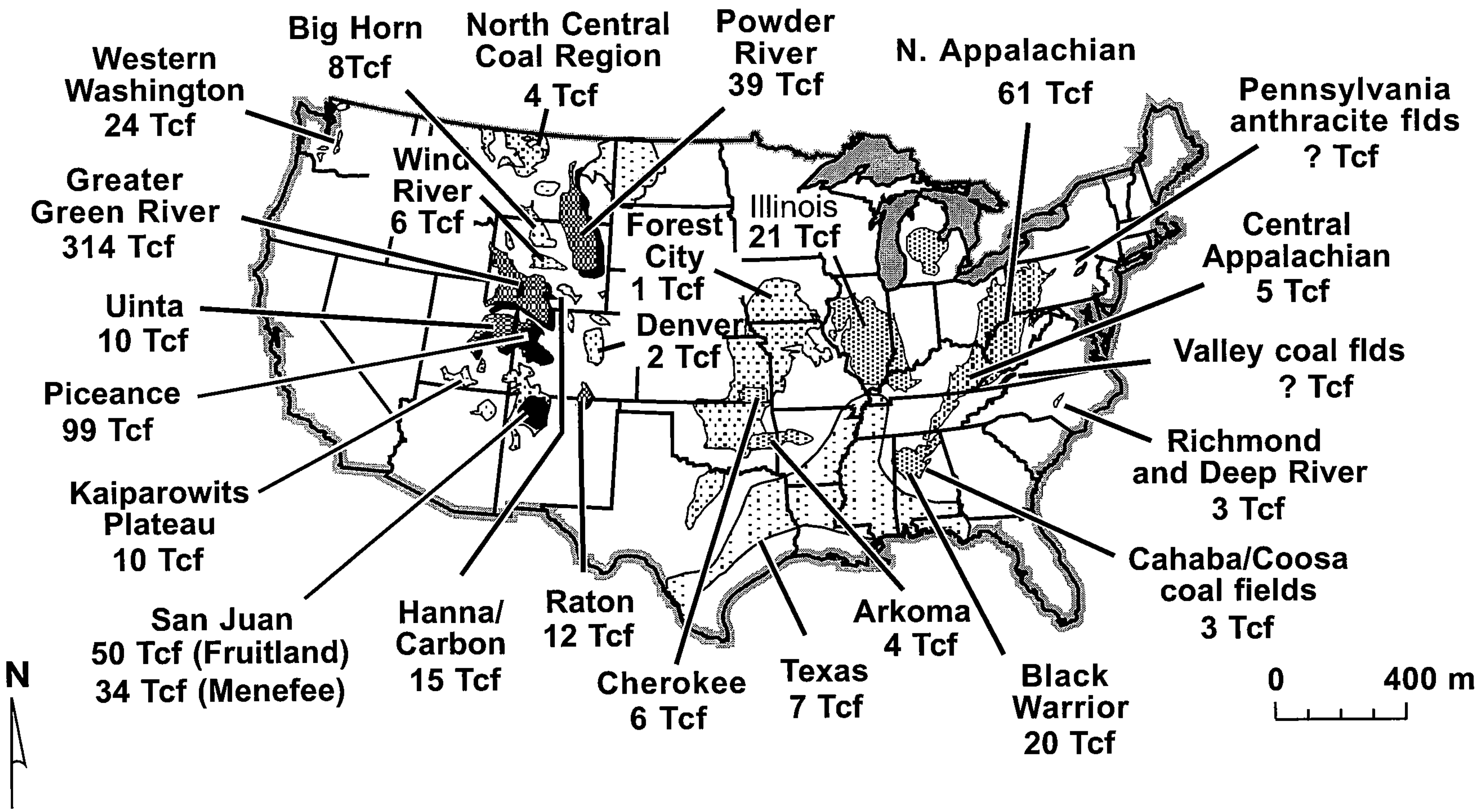

Figure 1. Coal basins and coalbed gas resources of the United States of America. Total coal gas resources are estimated at 755 Tcf (21.38 Tm^3). Alaska contains an estimated 1,037 Tcf (29.36 Tm^3).

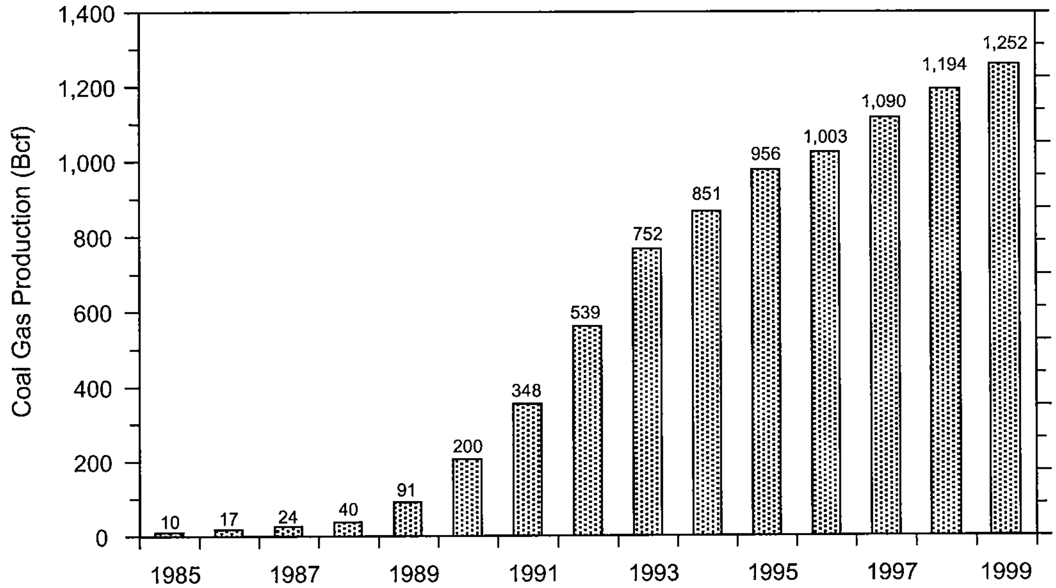

Figure 2. Coal gas production trends in the United States (Bryer and Guthrie, 1999). Total coal gas production has increased significantly since 1985 and currently exceeds 7% of the total dry gas production in the U.S.

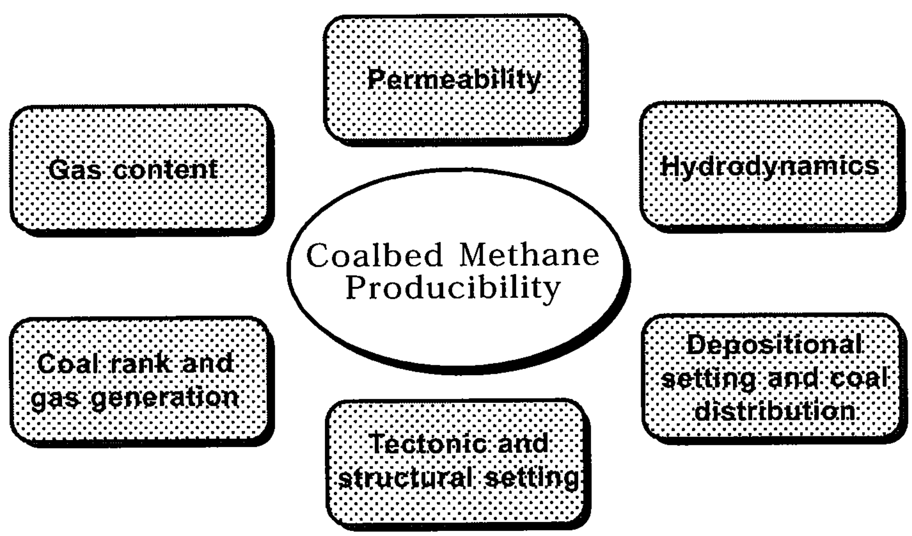

Figure 3. Geologic and hydrologic controls critical to coal gas producibility. A dynamic interaction among these key factors and their spacial relations governs producibility.

hydrodynamically trapped gases, in-situ-generated secondary biogenic gases, and solution gases are required to achieve high gas contents or fully gas saturated coals for consequent high productivity. To delineate the presence and origin of these additional sources of gas requires an understanding of the interplay among coal distribution, coal rank, gas content, hydrodynamics, depositional fabric, and structural setting (Kaiser and others, 1994; 1995).

Controls Critical to Coal Gas Producibility

Coalbed methane exploration strategies are often based only on the location of the greatest net coal thickness and ignore other hydrologic and geologic factors affecting coalbed methane producibility. Coalbed methane producibility is determined by the complex interplay among six critical controls: depositional systems and coal distribution, coal rank, gas content, permeability, hydrodynamics, and tectonic/structural setting (Figures 3 and 4)(Scott, 1999). If one or more of these key hydrogeologic factors is missing, then the potential for higher coalbed methane producibility will be reduced. However, the coalbed methane play may remain economically viable. For example, the Piceance Basin is characterized by exceptionally high gas content values (more than 700 scf/ton; 21.8 cm^3/g), but coalbed methane production has been limited because of low permeability. However, the Powder River Basin remains economically successful with gas contents generally less than 30 scf/ton (0.9 cm^3/g), because thick (more than 100 ft; 30 m) coal beds are present at shallow depths. A review of each hydrogeologic factor will be followed by examples from the San Juan and Greater Green River Basin.

Depositional Setting and Coal Distribution

Coal beds are the source and reservoir for methane, indicating that their widespread distribution within a basin is critical to establishing a significant coalbed methane resource. Coal distribution is closely tied to the tectonic, structural, and depositional settings (Figure 4a), because peat accumulation and preservation as coal require a delicately balanced subsidence rate that maintains optimum water-table levels but excludes disruptive clastic sediment influx. The depositional systems define the substrate upon which peat growth is initiated and within which the peat swamps proliferate. Net coal thickness trends and depositional fabric strongly influence migration pathways and the distribution of gas content. The depositional setting also controls the types of organic matter

(a)

DEPOSITIONAL SETTING AND COAL DISTRIBUTION	
Tectonic setting	Regionally affects geometry, occurrence, and thickness of coal beds
Hydrodynamics	Recharge and ground-water flow influenced by coal continuity and geometry
Permeability	Local permeability enhancement associated with compaction over sandstones
Gas content	Maceral composition affects gas sorption and desorption rates
Coal rank and gas generation	Maceral type affects hydrocarbon generation rates and types of hydrocarbons

(b)

TECTONIC AND STRUCTURAL SETTING	
Depositional setting	Regionally controls orientation, geometry, and occurrence of facies and coal beds
Coal rank and gas generation	Burial history, coalification, gas generation, and timing of cleat development
Gas content	Uplift and cooling produces undersaturation and possible degassing of coals
Permeability	Decreases with depth; cleat orientation; present-day in-situ stress; anticlines
Hydrodynamics	Hydrologic control on peat accumulation; uplift of basin margins for recharge; isolation of coals from outcrop

(c)

COAL RANK AND GAS GENERATION	
Gas content	Thermogenic gas generation may result in higher gas contents
Depositional setting	The presence of thick, thermally mature coals enhances coalbed methane producibility
Tectonic setting	Burial history controls coalification and thermogenic gas generation
Hydrodynamics	Wet gases and condensate converted into secondary biogenic methane by bacteria
Permeability	Cleat frequency and, therefore, permeability increase with increasing rank

(d)

GAS CONTENT	
Coal rank and gas generation	Generally increases with coal rank and depth; updip migration; diffusion coefficients
Depositional setting	Macerals affect gas sorption and desorption; shale seals; coal thickness and continuity
Tectonic setting	Conventional trapping of gases at faults and anticlines; burial history; diagenesis
Hydrodynamics	Secondary biogenic methane; high or low gas content at convergent flow; low gas content possible near recharge zone
Permeability	High permeability near recharge zone may allow flushing and low gas content

(e)

PERMEABILITY	
Hydrodynamics	Meteoric recharge and enhanced near outcrop; diagenesis in sands; low/high permeability detrimental
Tectonic setting	Decreases with depth; present-day in-situ stresses; enhancement with structures; fault barriers
Depositional setting	Enhancement through compaction; sands as barriers; coal pinch-out; macerals and cleats
Coal rank and gas generation	Cleat frequency increases with rank; annealing; cleats filled with bitumen and minerals
Gas content	High permeability and flushing; high gas content and moderate permeability

(f)

HYDRODYNAMICS	
Tectonic setting	Uplifted margins; faults as flow barriers; flow enhancement along structures; isolation of outcrop coals; in-situ stresses; cross flow
Depositional setting	Permeability contrasts associated with facies; coal aquifer continuity; macerals and cleats
Coal rank and gas generation	Ground-water flow through higher rank coals; updip migration thermogenic gases
Gas content	High with convergent flow and permeability barriers;
Permeability	Water production implies permeability; high and low permeability detrimental; bacteria

Figure 4. Synergistic interplay among the key geologic and hydrologic factors affecting producibility. (a) depositional setting and coal distribution, (b) tectonic and structural setting, (c) coal rank and gas generation (d) gas content, (e) permeability, and (f) hydroduynamics

(macerals) which affect sorption characteristics and the quantity of hydrocarbons produced from the coal. Knowledge of depositional framework enables predication of coalbed thickness, geometry, and continuity and, therefore, which potential coalbed methane resources.

Tectonic and Structural Setting

The tectonic and structural setting control of a basin control the distribution and geometry of coal beds in the basin during deposition, and therefore, exert a strong control on the lateral variability of maceral (Figure 4b). Both the burial history and stress direction control the timing of cleat development in various parts of the basin and the final orientation of face cleats. The basin burial history and variability of regional heat flow control coalification and the types and quantities of thermogenic gases generated from the coals. Additionally, present-day insitu stress directions may significantly affect coalbed methane producibility. Stress directions orthogonal to face cleats will lower permeabiliy, whereas stress directions parallel to face cleat orientation may enhance permeability. Uplift and basinal cooling often result in undersaturation with respect to methane in the coals and possible degassing of coal beds. Finally, the location and geometry of faults may strongly influence the recharge of meteoric water, and therefore, the generation of biogenic gases.

Coal Rank and Gas Generation

Coals must reach a certain threshold of thermal maturity (vitrinite reflectance values between 0.8 and 1.0 percent; high-volatile A bituminous) before large volumes of thermogenic gases are generated. The amount and types of coal gases generated during coalification are a function of burial history, geothermal gradient, maceral composition, and coal distribution within the thermally mature parts of a basin (Figure 4c). Gases in coal beds may also be formed through the process of secondary biogenic gas generation. Secondary biogenic gases are generated through the metabolic activity of bacteria, introduced by meteoric waters moving through permeable coal beds or other organic-rich rocks. Thus, secondary biogenic gases differ from primary biogenic gases because the bacteria are introduced into the coal beds after burial, coalification, and subsequent uplift and erosion of basin margins. The bacteria metabolize wet gas components, n-alkanes, and other organic compounds at relatively low temperatures (generally less than 150°F; 56°C) to generate methane and carbon dioxide. Secondary biogenic gases are known to occur in subbituminous through low-volatile bituminous and higher-rank coals (Scott, 1993; 1994).

Gas Content

Gas content, is one of the more important controls of coalbed methane producibility, yet often is one of the more difficult parameters to accurately assess. Gas content is not fixed, but changes when equilibrium conditions within the reservoir are disrupted and is strongly dependent upon other hydrogeologic factors and reservoir conditions (Scott and Kaiser, 1996) (Figures 4d and 5). The distribution of gas content varies laterally within individual coal beds, vertically among coals within a single well, and laterally and vertically within thicker coal beds (Figure 6). In general, gas content increases with depth and coal rank, but is often highly variable due to geological heterogeneities, the type of samples taken, and/or the analytical laboratory. The gas content of coals can be enhanced, either locally or regionally, by generation of secondary biogenic gases or by diffusion and long-distance migration of thermogenic and secondary biogenic gases to no-flow boundaries such as structural hingelines or faults for eventual resorption and conventional trapping (Figure 7). Therefore, determination of migration direction through isotopic and hydrogeologic studies is critical for determining migration direction and the areas of higher gas content.

Permeability

Permeability in coal beds is determined by its fracture (cleat) system, which is in turn largely controlled by the tectonic/structural regime as mentioned previously (Figure 4e). Cleats are the permeability pathways for migration of gas and water to the producing well head, and cleats may either enhance or retard the success of the coalbed methane completion. Permeability will decrease with increasing depth, suggesting that in the absence of structurally enhanced permeability at depth, coalbed methane production may be limited to depths less than 5,000 to 6,000 ft (1,524 to 1,829 m). Permeability is highly variable in coal beds ranging from darcies to microdarcies, but the most highly productive wells have permeability ranging between 0.5 to 100 md (Figure 8). Higher permeability will result in recovery of more sorbed coal gases, because lower reservoir pressures and, therefore, more coal gas desorption will occur in higher permeability reservoirs. However, permeability that is too high results in high

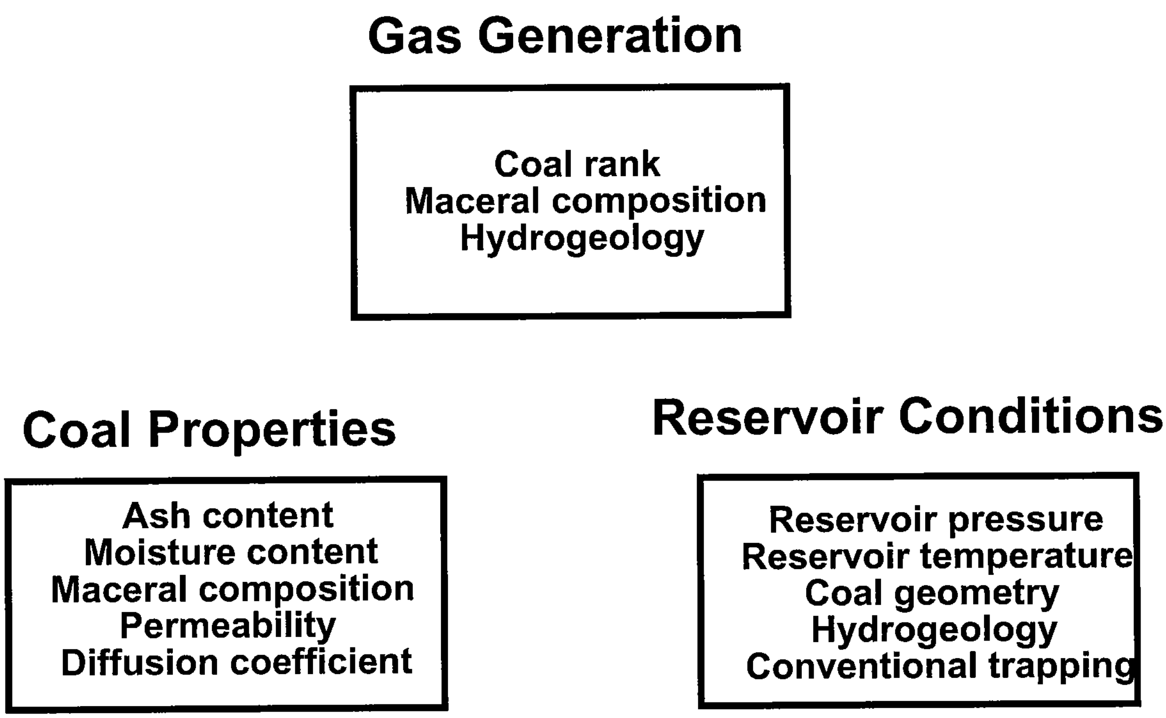

Figure 5. Primary factors affecting gas content distribution in coal beds (Scott and Kaiser, 1996). Gas content is not fixed, but changes when equilibrium conditions in the reservoir change.

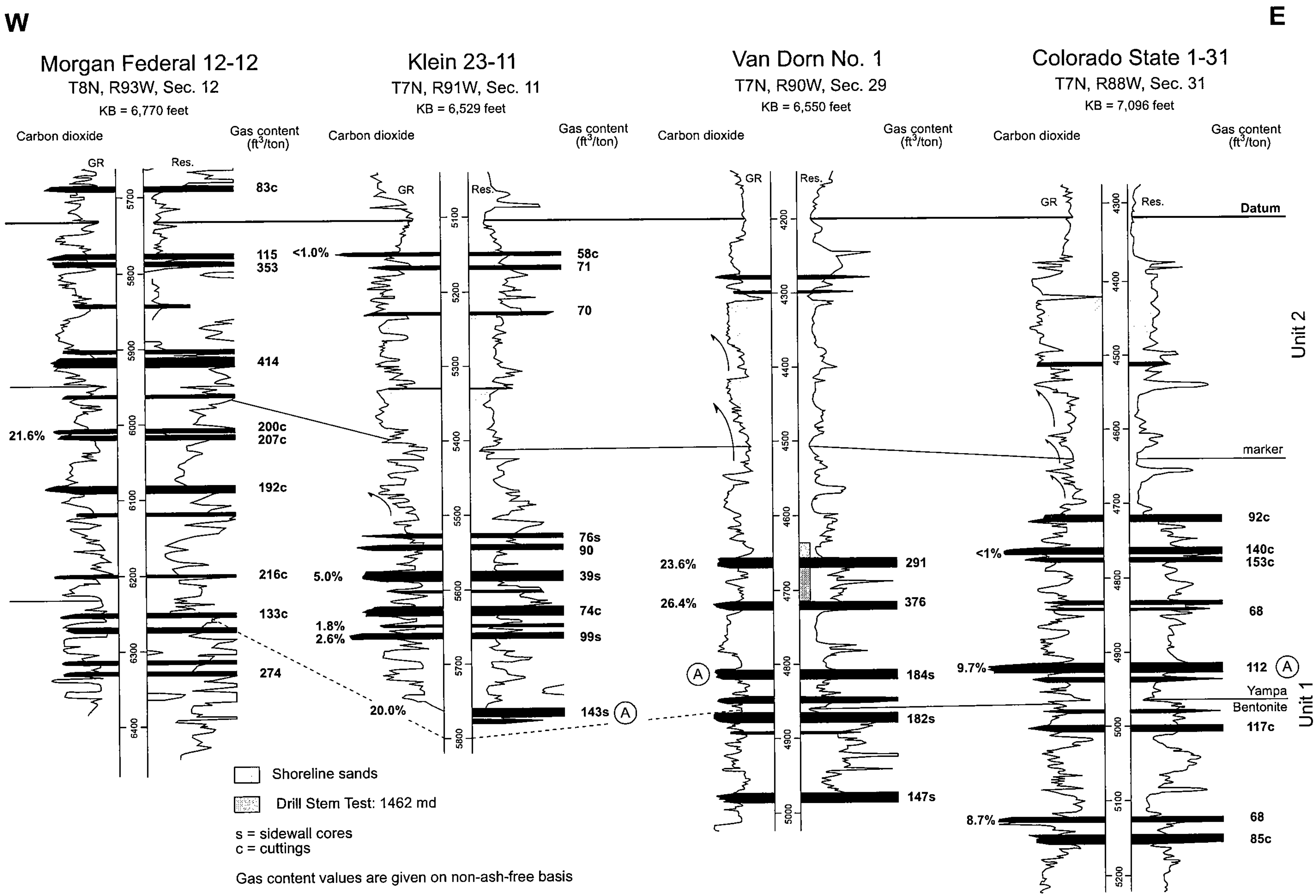

Figure 6. Cross section showing the changes in gas content and gas composition between wells in the Sand Wash Basin in Colorado.. The high gas content values at 5,900 ft (1,798 m) in the Morgan Federal 12-12 well may be due to trapping of upward migrating coal gases. From Scott (1993).

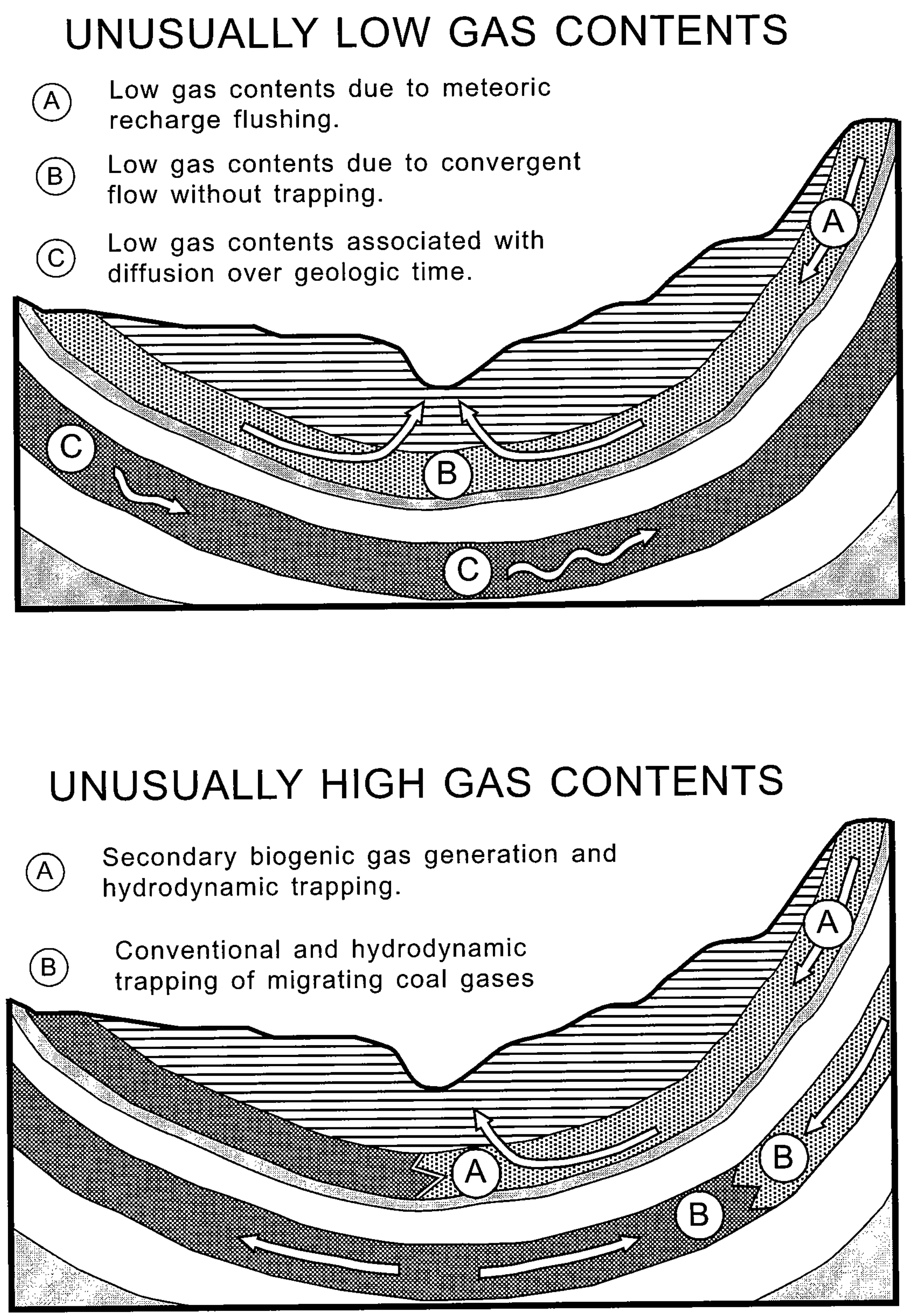

Figure 7. Fluid migration and the distribution of lower and higher gas contents.

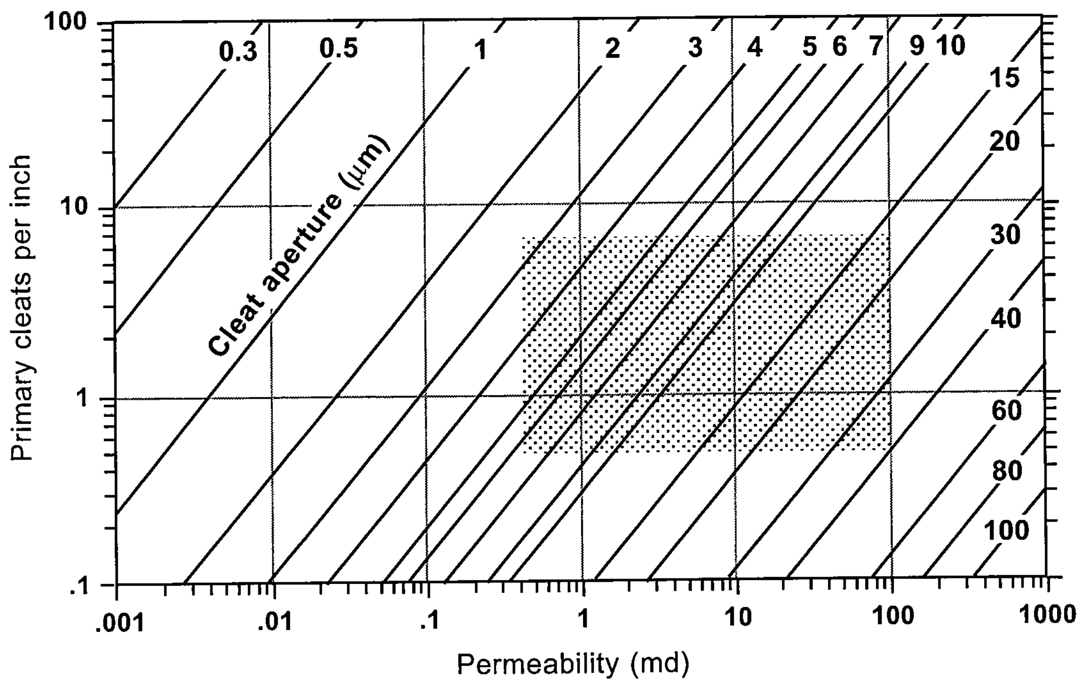

Figure 8. Relation among face cleat spacing, permeability, and face cleat aperture sizes based on cubic law equations from Lucia (1983) designed for fracture carbonate reservoirs. The stippled area represents the ranges of cleat spacing and permeability for highly productive coalbed methane wells in the San Juan and Black Warrior Basins. Modified from Scott (1995).

water production and may be as detrimental to the economic production of coalbed gas as extremely low permeability.

Hydrodynamics

Hydrodynamics strongly affects coalbed methane producibility and includes both the movement of meteoric water basinward as well as the migration of fluids from deeper in the basin. Basinward migration of ground water is intimately related to coal distribution and depositional and tectonic/structural setting because ground water movement through coal beds requires recharge of laterally continuous permeable coals at the structurally defined basin margins (Figure 4f). Coal beds act not only as conduits for gas migration but also are commonly ground-water aquifers having permeabilities that are orders of magnitude larger than associated sandstones. The presence of appreciable secondary biogenic gas indicates an active dynamic flow system with overall permeability sufficient for high productivity. Migration of thermogenic may result in abnormally high gas contents in lower rank coals or coals that are saturated or oversaturated with respect to methane.

Basin hydrogeology, reservoir heterogeneity, location of permeability barriers (no-flow boundaries), and the timing of biogenic gas generation and trap development are critical for exploration and development of unconventional gas resources in organic-rich rocks.

Resource Assessment

Accurately assessing coal and coalbed methane resources and delineating areas within basins that contain the largest resources are important aspects of resource development. The coalbed methane producibility model can be used to predict areas within basins that may have higher than expected gas contents. Gas content variability is one of the more difficult parameters to constrain during resource calculations (Scott and others, 1995). However, ash-free gas content data in addition to net coal thickness, coal rank, ash content, and ash-free and bulk coal density values can be contoured, digitized, and converted into a grid and note system for coal and coalbed methane resource calculations if sufficient data are available. Modified approaches to coal and coalbed methane resource calculations are required in the absence of sufficient data or well control.[18] Accurate assessment of resources and application of the producibility model may provide a basis for economic evaluation of coal and coalbed methane resources based on incremental increases in drilling depth. Additionally, specific areas in the basin having large gas resources can be delineated, providing a basis for future exploration efforts. Therefore, accurate determination of coalbed methane resources is important in assessing the potential of future coalbed methane production.

CONCLUSIONS

The complex interplay and spatial relationship among coal distribution, coal rank, gas content, permeability, hydrodynamics, and depositional and tectonic/structural setting govern the occurrence and production of coalbed methane. High productivity requires that these controls be synergistically combined. In the San Juan Basin, they are combined synergistically, resulting in prolific production because ground water flows through thick coals of high thermal maturity toward a structural hingeline (no-flow boundary). The relatively large volume of gas available in thermally mature coals and secondary biogenic gases generated by bacteria after uplift and basinal cooling are swept basinward for conventional trapping along the hingeline, providing additional sources of gas beyond that sorbed initially on the coal surface. Conventional trapping plays a much more important role in coalbed methane production than is generally recognized.

Pennsylvanian-age coals in Cherokee, Forrest City, and Arkoma basins have generally reached the thermal maturity level required to generate significant quantities of methane. Secondary biogenic methane generation may have occurred near the outcrop, but the apparent presence of predominantly saline waters in the Cherokee and Arkoma Basin coupled with relatively low water production suggests that secondary biogenic methane generation may be limited. The presence of wells with exceptionally high production is encouraging and suggests that adequate permeability exists at depth. The biggest limiting factor for coalbed methane development appears to be net coal thickness. However, gas production from carbonaceous shales and/or adjacent sandstones may enhance the economic viability of coalbed methane wells.

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Arkansas coal geology and potential for coalbed methane

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INTRODUCTION

Coal is a solid fossil fuel, which was first discovered and utilized in Arkansas in the early 19th century. Because of its solid nature, coal has traditionally been mined in order to be used. Coal is classified according to the percentage of fixed carbon it contains on a dry mineral-matter-free basis and the amount of heat it gives off when completely burned, measured in British Thermal Units (Btu's; Table 1).

The Arkansas coalfields lie within the Arkansas Valley physiographic province of northwestern and north-central Arkansas (Figure 1). Coal rank increases from low-volatile bituminous to semianthracite from west to east. This coal has been used to produce steam for electric power generation, steam locomotives, heating of homes, coking or metallurgical coal for making steel, and as chemical feedstock in making chemicals. As of 1999, over 106 million short tons of coal have been mined in Arkansas for these various uses. During the last two decades of the 20th century, only small locally owned mines have produced coal for use in charcoal briquettes, in pipeline coatings, and by blacksmiths. During the 1990s, yearly coal production in Arkansas was less than 100,000 tons per year (Bush, 2000). Recoverable reserves are estimated to be about 1 billion tons.

Sources of Information

The information for this report was obtained from reports of previous workers. Especially important reports were by Haley, Hendricks, and Mereweather of the U.S.

Geological Survey, and Bush, Colton, and Gilbreath of the Arkansas Geological Commission. Early 20th-century coal reports by Steel (1910) of the University of Arkansas have also provided useful information.

STRATIGRAPHY

The coal-bearing formations are in the Arkoma basin in western Arkansas. This sedimentary basin trends east-west and occupies the same area as the Arkansas Valley physiographic province.

The basin contains sedimentary rocks ranging in age from Upper Cambrian to Middle Pennsylvanian (Haley, 1982). The basin is located between the Ozark Plateaus on the north and the Ouachita Mountains on the south. The sedimentary sequence thickens to the south where it reaches a maximum thickness of over 25,000 feet. Deposition was, for the most part, in a marine environment (Haley, 1982). The coal-bearing formations are, in ascending order: Atoka, Hartshorne, McAlester, and Savanna (Figure 2). The Atoka Formation is part of the Atokan Series; the Hartshorne, McAlester, and Savanna Formations are of the Desmoinesian Series.

Atoka Formation

The Atokan rocks consist lithologically of about 70% shale, 20% sandstone, and 10% siltstone. These rock types typically occur as repetitive coarsening-upward sequences of shale to siltstone to sandstone. This sequence is generally recognized as belonging to deltas prograding into a marine environment. The Atoka Formation has been subdivided into upper, middle, and lower units based on mappable lithologies of shale and sandstone (Haley, 1982). At the top of some sandstones in the upper Atoka Formation are thin discontinuous coals, which indicate that some areas were above sea level by upper Atoka time. The Atoka Formation ranges from 4,000 to an estimated 22,000 feet thick.

Hartshorne Sandstone

The Hartshorne Sandstone unconformably overlies the Atoka Formation (Haley, 1982). The Hartshorne is largely composed of massive medium-grained sandstone. It is the most continuous and widespread of all Desmoinesian sandstones. The Hartshorne Sandstone was deposited as part of a westward-flowing meandering river (Haley, 1982). In some areas, the Hartshorne contains thin shales that may contain thin coals (less than 1 foot thick). The Hartshorne ranges from 10 to 300 feet thick.

McAlester Formation

Conformably overlying the Hartshorne Sandstone, the McAlester Formation contains several coal beds. The Lower Hartshorne coal, the most important coal bed in Arkansas, is the most continuous and thickest of the Arkansas Valley coals and therefore the one most mined. The Lower Hartshorne coal occurs near the base of the McAlester Formation, 1 to 5 feet above the Hartshorne Sandstone. The McAlester Formation is composed primarily of shale with a few thin sandstone beds (Haley, 1982). The Upper Hartshorne coal occurs 40 to 90 feet above the Lower Hartshorne coal. The two coals are not known to wedge together in Arkansas as they do in Oklahoma. The McAlester Formation ranges from 500 to 2,300 feet thick (Haley, 1982).

Savanna Formation

The Savanna Formation contains several thin coals, but only two coals have been of minable importance. The Charleston coal is near the base of the formation, and the Paris coal is in the upper part. The Savanna Formation encompasses primarily dark gray shale and silty shale. Minor amounts of siltstone and sandstone occur throughout the section. The Savanna Formation may be as thick as 1,600 feet in Arkansas (Haley, 1982).

Boggy Formation

The Boggy Formation contains no coal and only 225 feet of the lowermost part of the formation occurs in Arkansas. Occurring in isolated remnants, the Boggy Formation is composed of silty sandstones and thin beds of siltstone and shale.

STRUCTURE

The Arkansas Valley coalfields within the Arkoma basin contain anticlines, synclines, and normal and thrust faults. All trend generally east-west (Haley, 1982).

Folds

Numerous anticlines and synclines exist within the basin (Figure 3). Dips of the rocks can be as low as 10 degrees along the flank of these folds in the northern part. However, dips may increase to 35 degrees close to normal faults. In the more structurally complex southern areas of the basin, north-side dips of anticlines may reach 15 degrees beyond vertical (Haley, 1982). These structures have played a major role in the distribution of the coals within the basin. Along the hinge lines or centers of the anticlines, the coal beds may have been removed by erosion, while the coal beds may be hundreds to as much as 3,000 feet deep in the axis of synclines (Haley, 1960).

Faults

Parts of the northern boundary of the Arkoma basin are marked by the Mulberry fault, which has as much as 2,500 feet of displacement along townships 9 north and 10 north (Figure 4).

The faults in the northern and central parts of the basin are normal "growth" faults (Figure 4), which formed during the deposition of the sediments. The downthrown side of these faults are generally on the south side; dips range from 30 to 65 degrees to the south (Haley, 1982). North-dipping normal faults also are present, but are thought to be antithetic to the south-dipping faults. North-dipping faults do not appear to have the same amount of displacement (Haley, 1982).

Near the frontal Ouachita Mountains along the southern margin of the basin, low- and high-angle thrust faults exist, many along the crest of anticlines. These thrust plates have been moved to the north (Haley, 1982).

ARKANSAS VALLEY COAL BEDS

Coal reserve and resource estimates have been made only for the four major coal beds which have been mined. These beds are the Lower and Upper Hartshorne coal, Charleston coal, and Paris coal (Haley, 1987). As previously mentioned, there are coal beds in the upper Atoka Formation, but these coals seem to be thin and discontinuous. One coal in the Atoka Formation was mined near Centerville in Yell County for local use only (Haley, 1960).

Lower Hartshorne Coal

The Lower Hartshorne coal is the most widespread and most produced coal in Arkansas, containing about 94% of the total coal resource (Haley, 1987). It extends over an area of 1,300 square miles (Figure 5). Coal thickness varies, with areas of 14 inches or thicker covering an area of about 740 square miles (Figure 5; Haley, 1960). It is reported to be more than 8 feet thick near Huntington in Sebastian County (Haley, 1960).

Overburden has largely been controlled by structure (Figure 5), with some of the greatest depths occurring in the axis of synclines. Coal is present at the surface where younger overlying sedimentary strata has been eroded.

Upper Hartshorne Coal

The Upper Hartshorne coal occurs over an area of approximately 28 square miles. It is 14 inches or more thick in an area of 16 square miles (Figure 6; Haley, 1960) and has a maximum thickness of 34 inches. Figure 6 also shows the estimated thickness of overburden for the Upper Hartshorne coal in southern Sebastian County.

Charleston Coal

The Charleston coal extends about 120 square miles (Figure 7) in parts of northern Sebastian and Logan Counties and is more than 14 inches thick over an area of 52 square miles (Haley, 1960). The Charleston coal has a maximum thickness of 23 inches (Haley, 1960). Overburden thickness is, in large part, controlled by local structure.

Paris Coal

The Paris coal occurs in three small areas in Franklin and Logan Counties (Figure 8; Haley, 1960). In the largest area in Logan County, the Paris coal ranges from 14 to 32 inches thick.

Coal Quality and Rank

As in Oklahoma, coal rank in the Arkansas Valley coalfields increases from west to east. There have been various explanations as to why this occurs, but none seem totally conclusive.

About 80% of Arkansas Valley coal are low-volatile bituminous rank. The rank line, drawn on the basis of coal sample testing, runs across central Logan County through western and central Johnson County (Figures 5 to 8). This line divides coal beds based on greater than or less than 86% fixed carbon.

Table 2 shows proximate analyses of the various coal beds that occur in the Arkansas Valley coalfields (Howard and others, 1997).

COALBED METHANE: "FIREDAMP"

Firedamp was the term used for methane gas (CH4) which occurred in underground coal mines in the early 20th century. It was reported to have been encountered in small pockets. In 1906–1908, firedamp caused the deaths of at least 3 miners in Arkansas (Steel, 1910). Today, coalbed methane is viewed as a new source of energy from deeply buried coal beds.

Unfortunately, little modern work has been done on the coalbed-methane potential of the Arkansas Valley coalfields. Rieke and Kirr (1984) gave a geologic overview on the coalbed-methane potential for the Arkoma basin in Oklahoma and Arkansas. However, the information about the gas-producing potential of individual coal beds in Arkansas is unknown. Such factors as gas content, cleat direction and spacing, and water content have not been reported for Arkansas as has been done in Oklahoma. The early 20th century reports of A.A. Steel about underground coal mining may offer some insight into some of these factors.

One factor in coalbed-methane production is cleating or fracturing within the coal bed. Old-time miners used to refer to these as "slips." Cleats or slips are important pathways to allow gas released from the coal to migrate and be collected at the well. Steel (1910) reported, "All slips have a direction of strike between north and northwest." Figure 9 shows the cleats relative to the mining front. Figure 10 shows the "two sets not equally marked dipping in opposite directions." These "slips" were reported on because of their effects on the blasting needed to loosen the coal before it could be mined. Steel (1910) also reported that the Lower Hartshorne coal was like "woody coal" which did not always blast apart well.

Another factor, which Steel reported, was that the coal mines contained methane. No quantitative measurements were done but gas was reported to have occurred in small pockets. Also, not as much gas was encountered compared to some other United States coalfields possibly because the Arkansas underground coal mines generally were not as deep as in many other coal-mining regions.

Also affecting coalbed-methane production is the condition of the surrounding rock layers above and below the coal beds. Steel (1910) reported that, in most cases, the roof was solid, but in some areas the roof was crumbly. Between 1906 and 1908, 62% of the miners were killed by rockfalls in Arkansas.

The last factor controlling gas production is the amount of water present in the coal bed. An estimated 39,000 to 46,000 acre-feet of water was calculated to exist within the abandoned underground coal mines (Potts, 1987). Some sites produced surface flowage of 75 to 460 gallons per minute (Potts, 1987).

Water quality was variable; dissolved solids range from 70 to 1,550 mg/liter and pH is 3.2 to 7.9 with a medium of 6.5 Dissolved solids such as sulfate, calcium, sodium, and magnesium affect the water quality the most (Potts, 1987). Some water was good for all uses while others were only good for restricted use (Potts, 1987). Depths to salt water range from 500 to 2,000 feet with an average depth of 1,000 feet based on information from gas well logs (Cordova, 1963).

LIGNITE: "ARKANSAS' OTHER COAL"

In the Gulf Coastal Plain of eastern and southern Arkansas (Figure 11) there are lignite coal deposits. Lignite is the next to lowest rank of coal (Table 1). Arkansas lignite averages 6,932 Btu/lb on a moist, mineral-matter-free basis (Prior and others, 1985).

Arkansas lignite occurs in large deposits in two units. The Wilcox Group is Eocene in age, is composed of sand, clay, and silt, and is about 800 feet thick. Lignite beds tend to be lenticular with some beds up to 10 feet thick (Prior and others, 1985). Lying above the Wilcox Group, the Claiborne Group is also of Eocene age, is composed of sand, silt, and clay, and is about 1,200 feet thick. Lignite beds of up to 10 feet thick are also reported to occur in the Claiborne Group (Prior and others, 1985).

A total of 9 billion tons of lignite resources is estimated to exist within 156 feet of the surface. The distribution and quantity of lignite at greater depths is unknown.

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CLASS	GROUP	Limits of fixed carbon or Btu mineral-matter-free basis	Requisite physical properties
I. Anthracitic	1. Meta-anthracite	Dry FC 98 percent or more (dry VM, 2 percent or less).	
	2. Anthracite	Dry FC, 92 percent or more and less than 98 percent (dry VM, 8 percent or less and more than 2 percent).	
	3. Semianthracite	Dry FC, 86 percent or more and less than 98 percent (dry VM, 14 percent or less and more than 8 percent).	Nonagglomerating.
II. Bituminous	1. Low-volatile bituminous coal.	Dry FC, 78 percent or more and less than 86 percent (dry VM, 22 percent or less and more than 22 percent).	
	2. Low-volatile bituminous coal.	Dry FC, 69 percent or more and less than 78 percent (dry VM, 31 percent or less and more than 22 percent).	
	3. Medium-volatile A bituminous coal.	Dry FC, less than 69 percent (dry VM, more than 31 percent); and moist Btu, 14,000 or more.	
	4. High-volatile B bituminous coal	Moist Btu, 13,000 or more and less than 14,000.	
	5. High-volatile C bituminous coal.	Moist Btu, 11,000 or more and less than 13,000.	Either agglomerating or non-weathering.
III. Subbituminous	1. Subbituminous A coal.	Moist Btu, 11,000 or more and less than 13,000.	Both weathering and nonagglomerating.
	2. Subbituminous B coal.	Moist Btu, 9,500 or more and less than 11,000.	
	3. Subbituminous C coal.	Moist Btu, 8,300 or more and less than 9,500.	
IV. Lignite	1. Lignite	Moist Btu, less than 8,300.	Consolidated.
	2. Brown coal.	Moist Btu, less than 8,300.	Unconsolidated.

Table 1. Classification of coals by rank. (Symbols FC - fixed carbon; VM - volatile matter; Btu - British thermal units. From American Society of Testing and Materials, 1939, p 2.)

Coal bed	Number of samples	County	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Heat of combustion in Btu's
Charleston	5	Franklin, Sebastian	2.4	18.2	74.0	5.5	2.6	14,363
Paris	43	Franklin, Logan	1.8	17.9	70.6	9.8	2.4	13,765
Atoka	3	Johnson, Pope	1.4	13.8	77.2	7.6	3.4	14,070
Lower Hartshorne	125	Scott, Sebastian	2.9	17.4	72.1	7.7	1.3	13,771
Lower Hartshorne	68	Franklin, Johnson	3.0	13.5	75.9	7.6	1.8	13,854
Lower Hartshorne	14	Logan, Pope	2.8	12.0	75.7	9.6	1.7	13,499

Table 2. Average analyses of Arkansas coals, in weight percent, as received from the mines. (Howard and others, 1997).

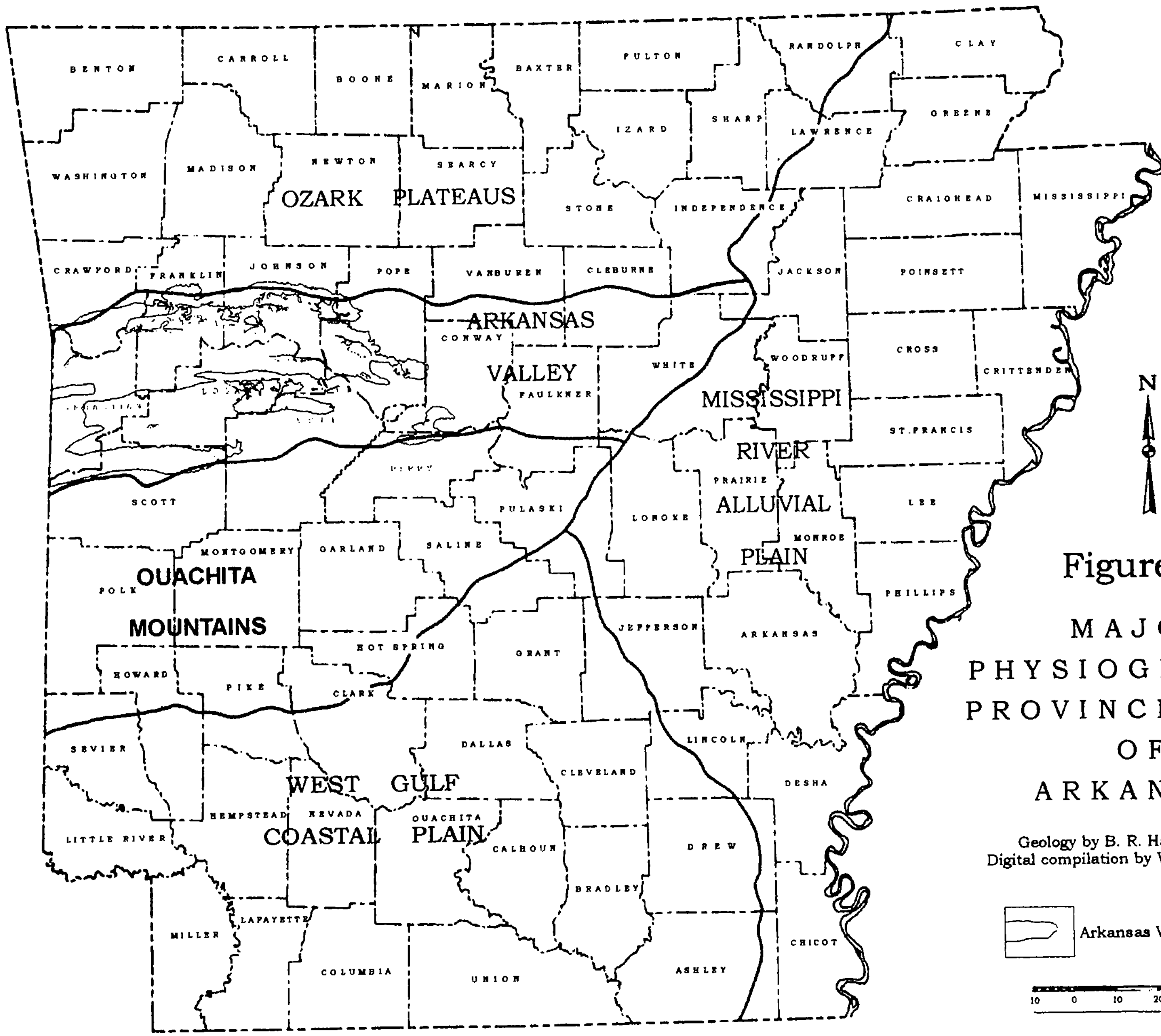


Figure 1

MAJOR PHYSIOGRAPHIC PROVINCES MAP OF ARKANSAS

Geology by B. R. Haley, 1960
Digital compilation by Walter Mayfield

Arkansas Valley Coal Field

10 0 10 20 30 40 MILES

ARKANSAS GEOLOGICAL COMMISSION

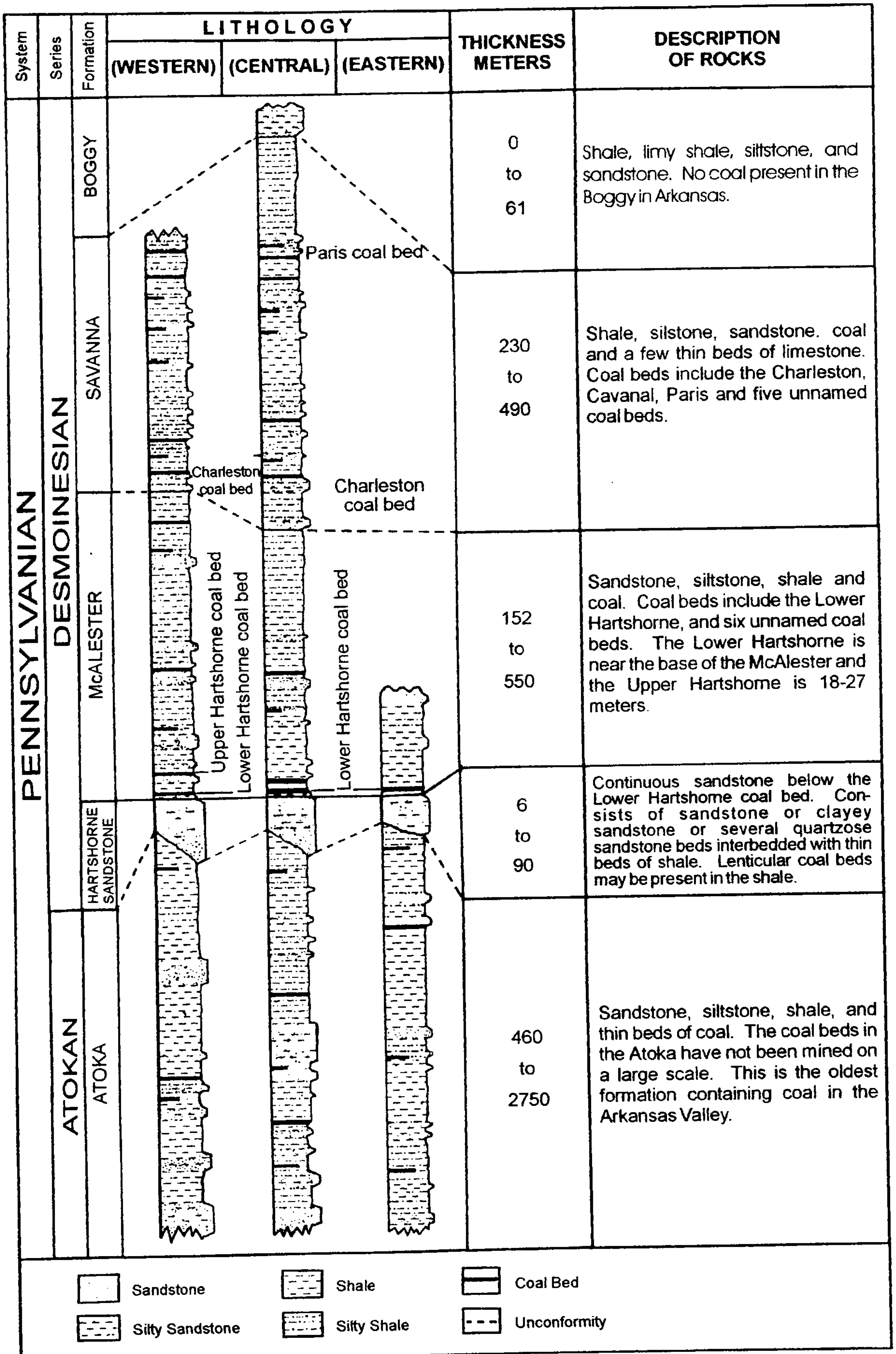


Figure 2. Generalized stratigraphic sections in the Arkansas Valley coal field. (Modified from Bush & Colton, 1983).

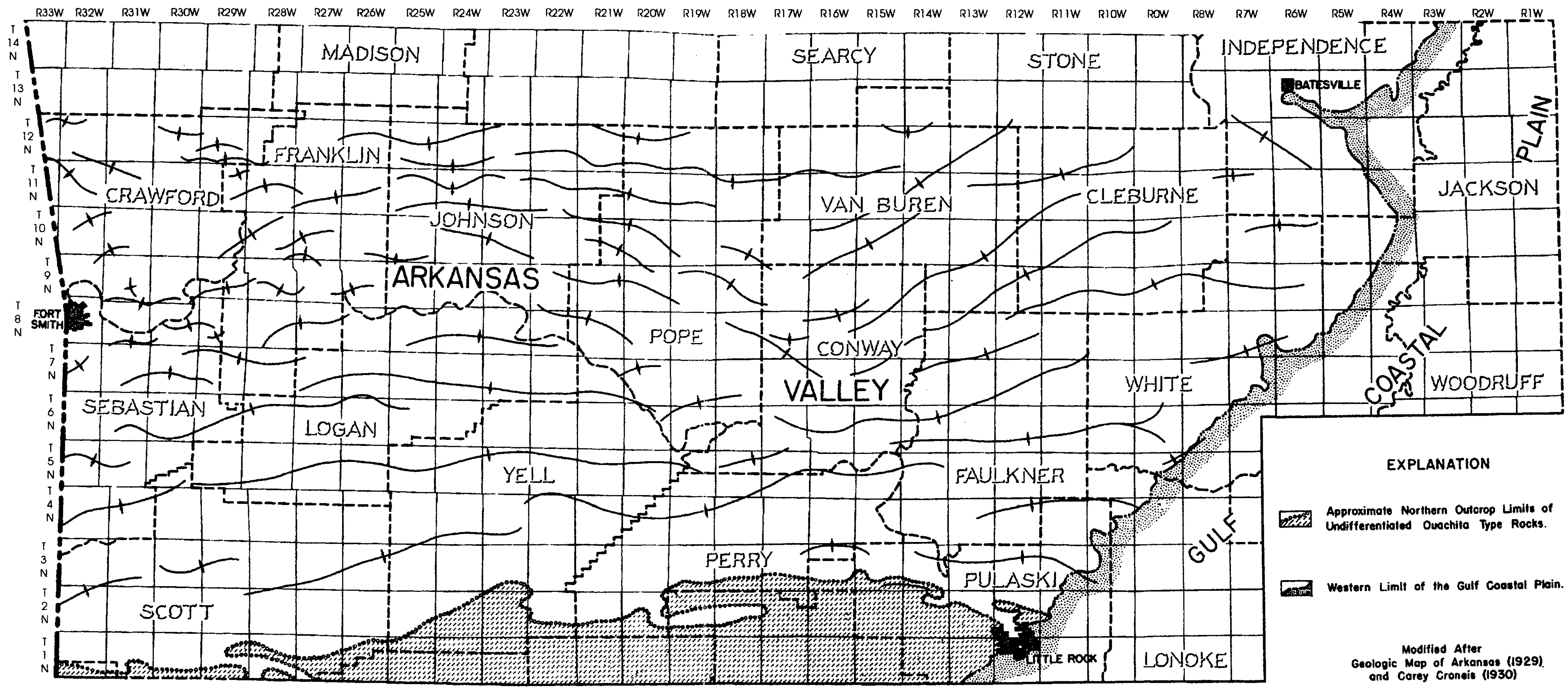


Figure 3
ANTICLINE AXES IN THE ARKANSAS VALLEY

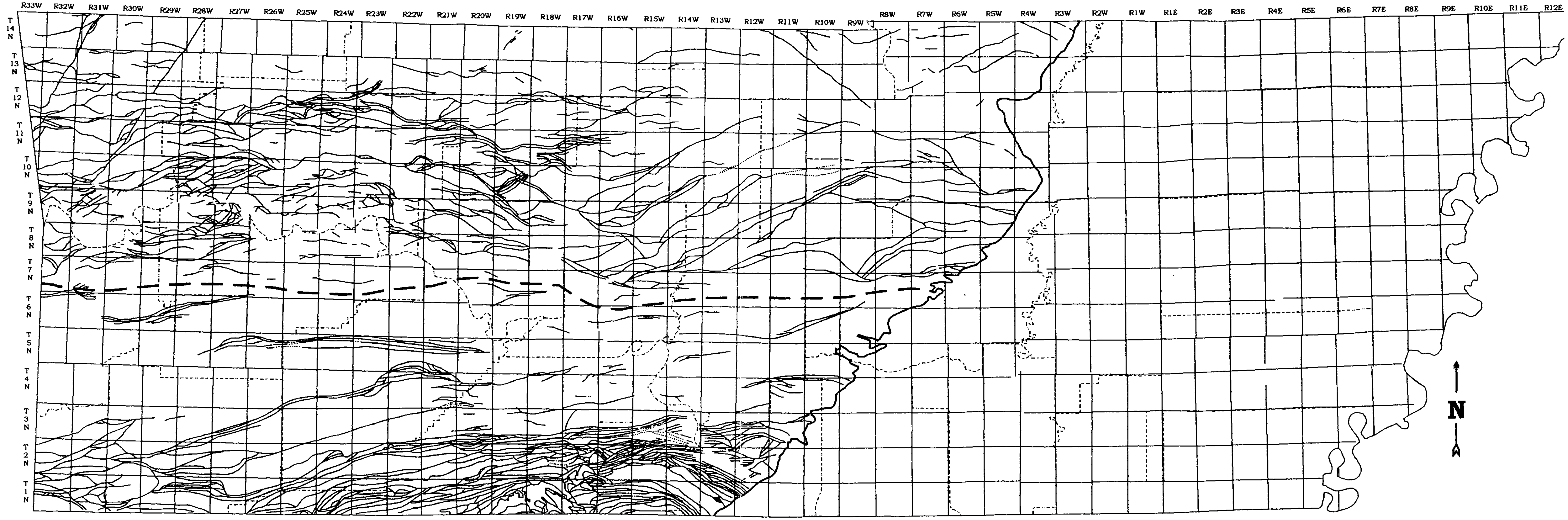


Figure 4

ARKANSAS BASE FAULTS MAP

EXPLANATION

Fault Lines

County Boundies

Boundary between Arkansas Valley Region normal faults to the north and thrust faults to the south.

Physiographic Fault Line

Geology Taken From Arkansas State Geologic Map 1993
Digital compilation by Jerry Clark

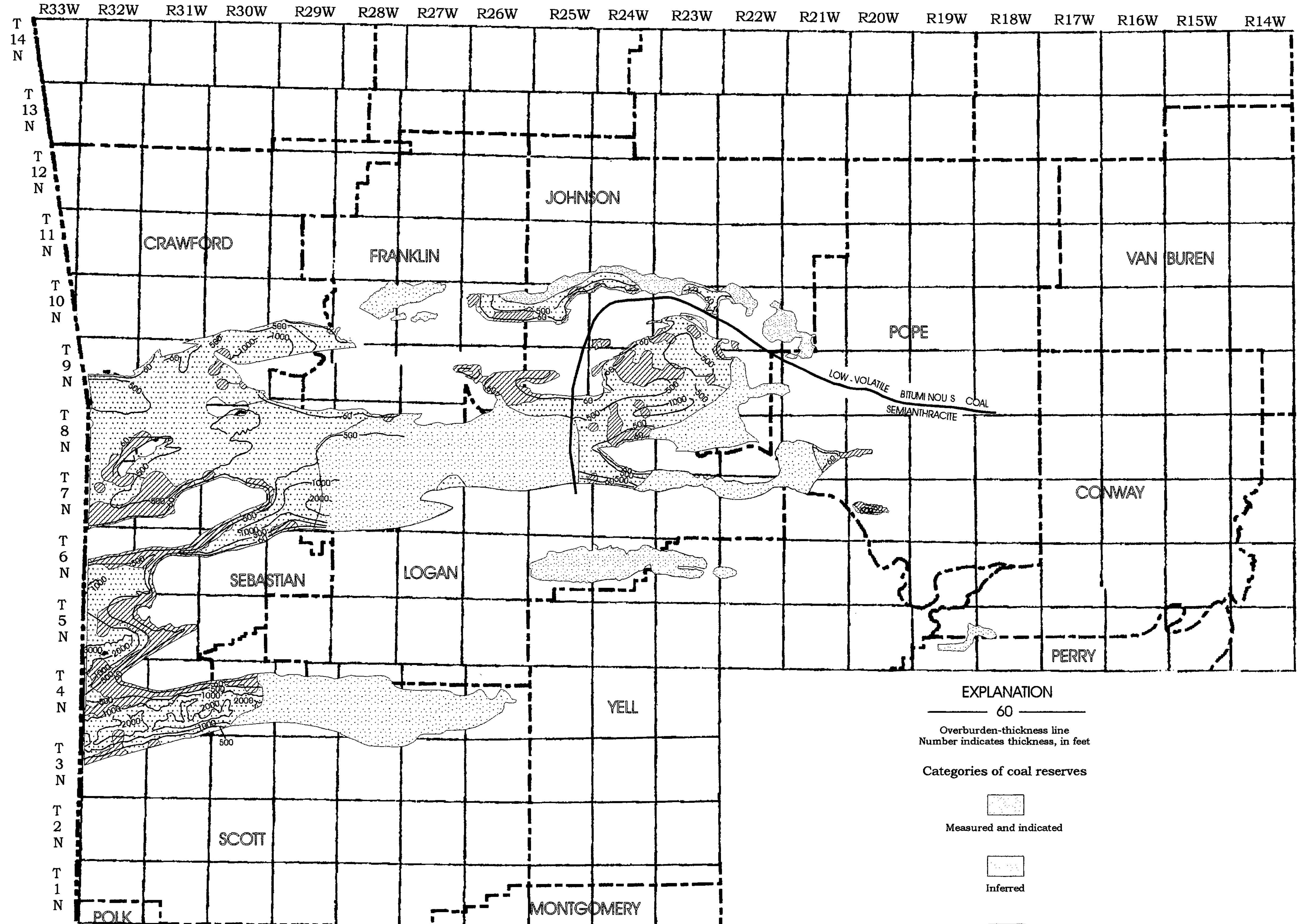


Figure 5-A

GENERALIZED MAP OF THE LOWER HARTSHORNE COAL BED IN ARKANSAS VALLEY COAL FIELD, ARKANSAS

EXPLANATION

60

Overburden-thickness line
Number indicates thickness, in feet

Categories of coal reserves

Measured and indicated

Inferred

Coal less than 14 inches thick, or data insufficient to estimate reserves

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

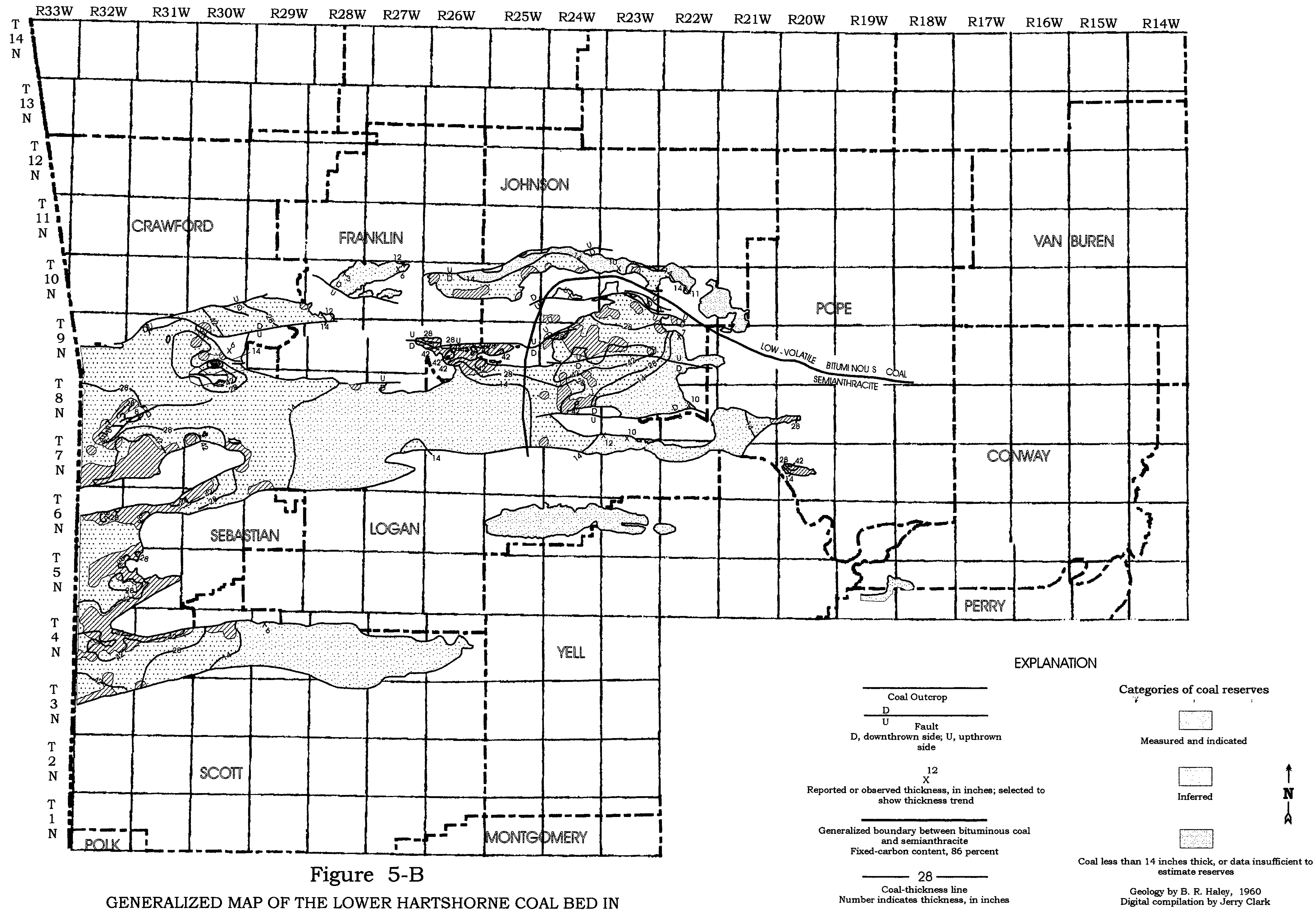


Figure 5-B

GENERALIZED MAP OF THE LOWER HARTSHORNE COAL BED IN ARKANSAS VALLEY COAL FIELD, ARKANSAS

(Modified from Haley, 1978 Plate 1)

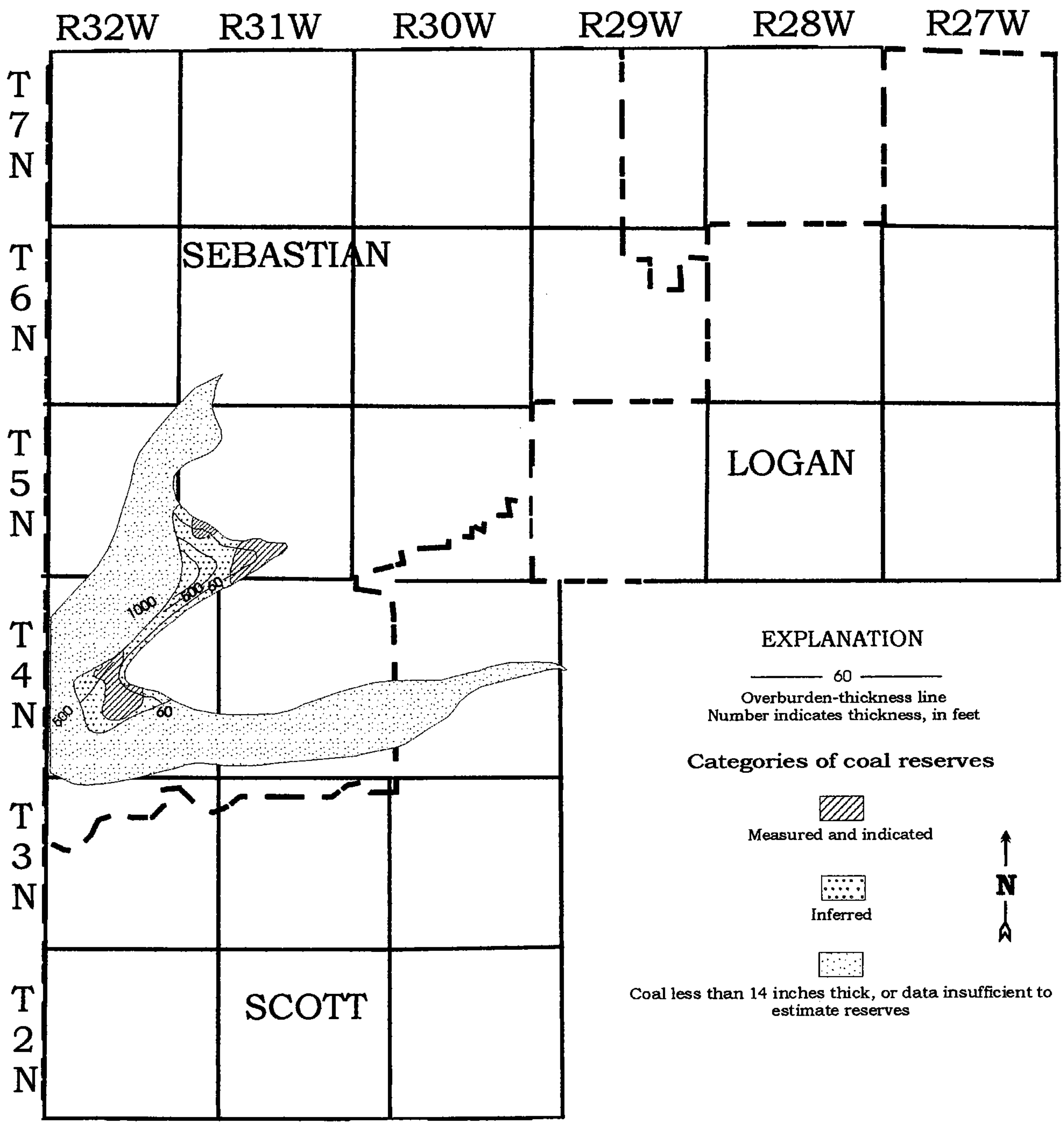


Figure 6-A

UPPER HARTSHORNE COAL BED

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

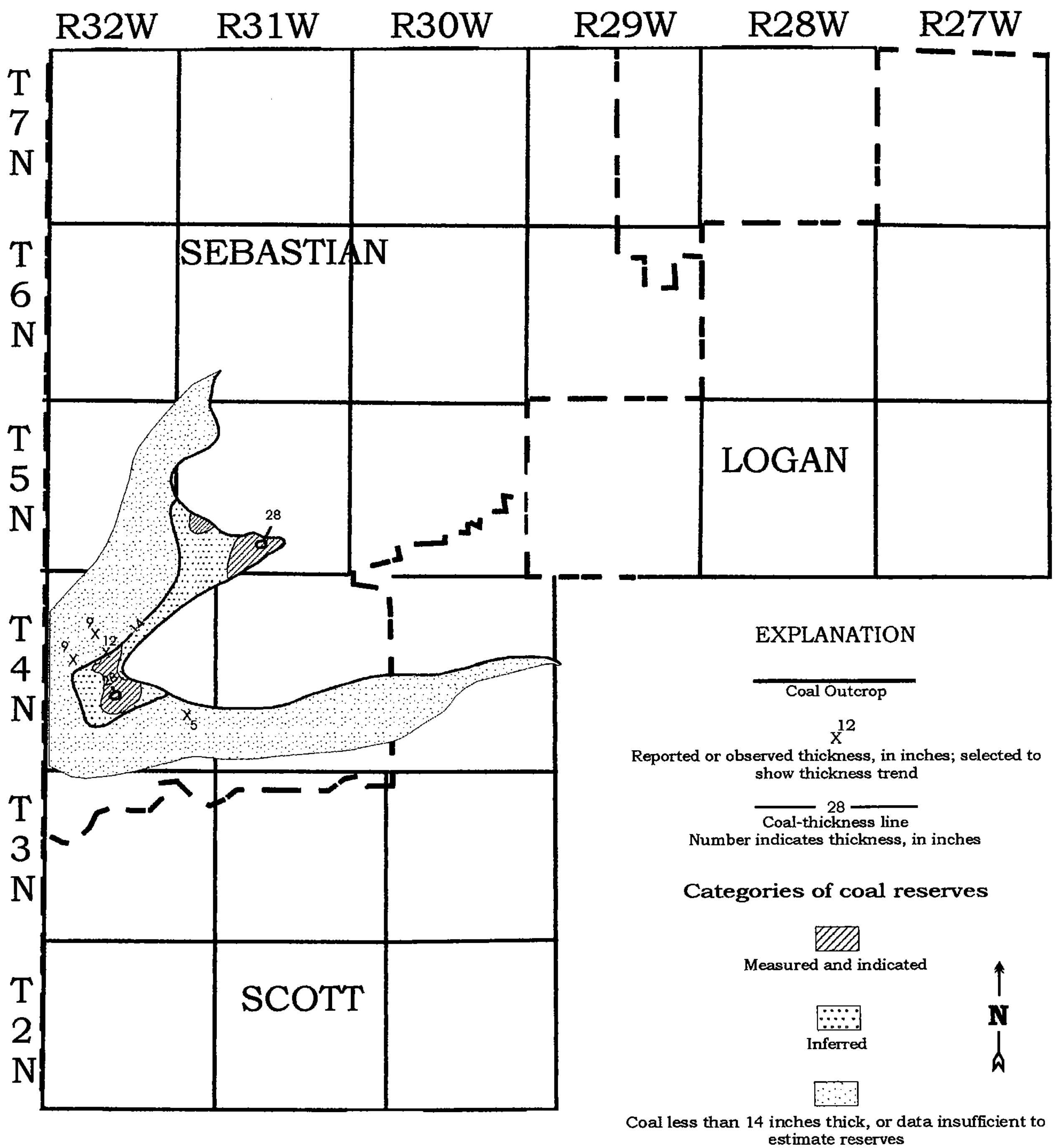


Figure 6-B

UPPER HARTSHORNE COAL BED

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

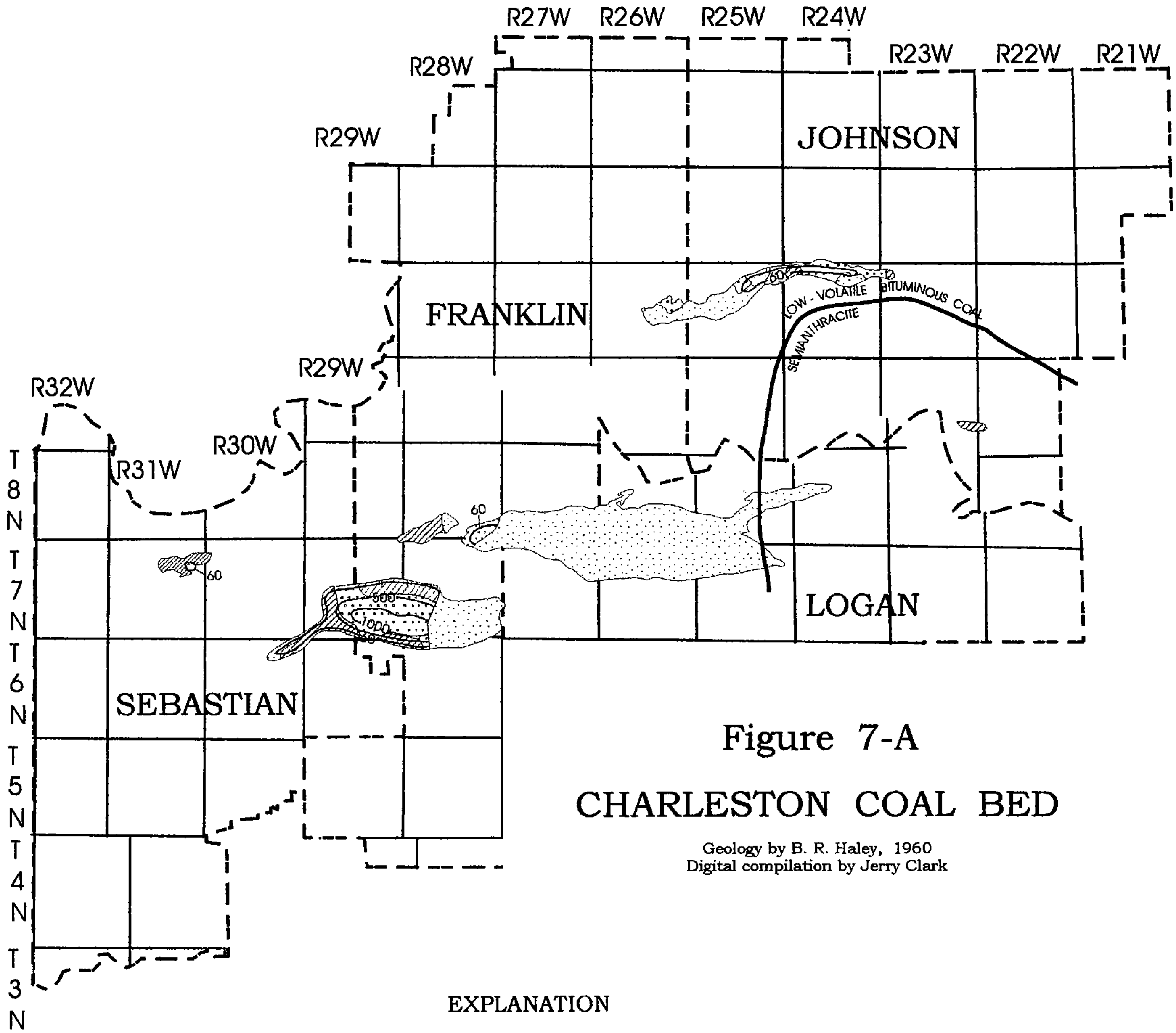


Figure 7-A

CHARLESTON COAL BED

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

EXPLANATION

——1000——
Overburden-thickness line
Number indicates thickness, in feet

Categories of coal reserves

Measured and indicated

Inferred

Coal less than 14 inches thick, or data insufficient to estimate reserves

N

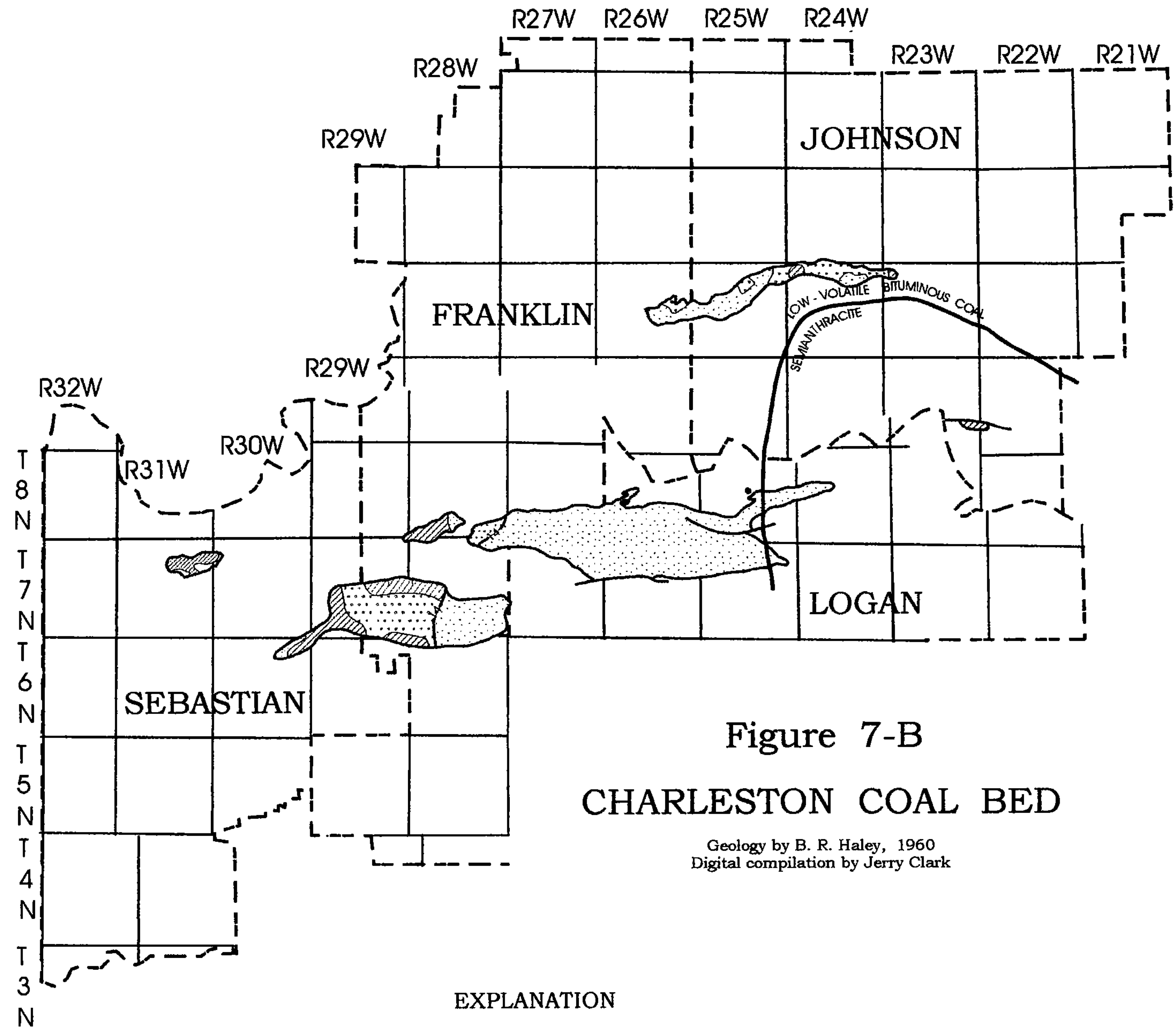


Figure 7-B

CHARLESTON COAL BED

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

EXPLANATION

Coal Outcrop

Fault
D, downthrown side; U, upthrown side

X^3
Reported or observed thickness, in inches; selected to show thickness trend

Generalized boundary between bituminous coal and semianthracite
Fixed-carbon content, 86 percent

28
Coal-thickness line
Number indicates thickness, in inches

Categories of coal reserves

Measured and indicated

Inferred

Coal less than 14 inches thick, or data insufficient to estimate reserves

N

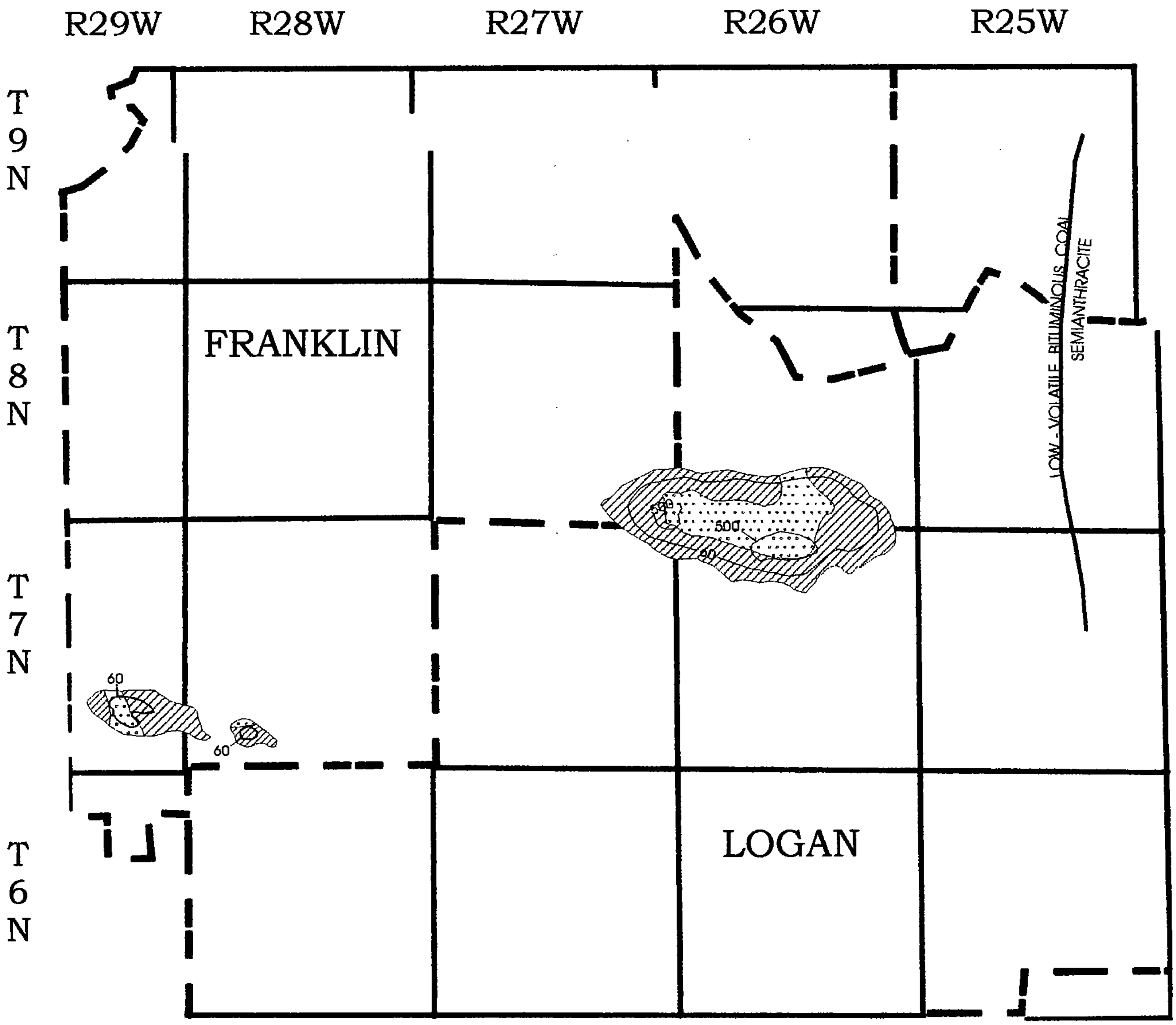


Figure 8-A

PARIS COAL BED

EXPLANATION

——— 60 ———

Overburden-thickness line
Number indicates thickness, in feet

Categories of coal reserves

Measured and indicated

Inferred

N

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

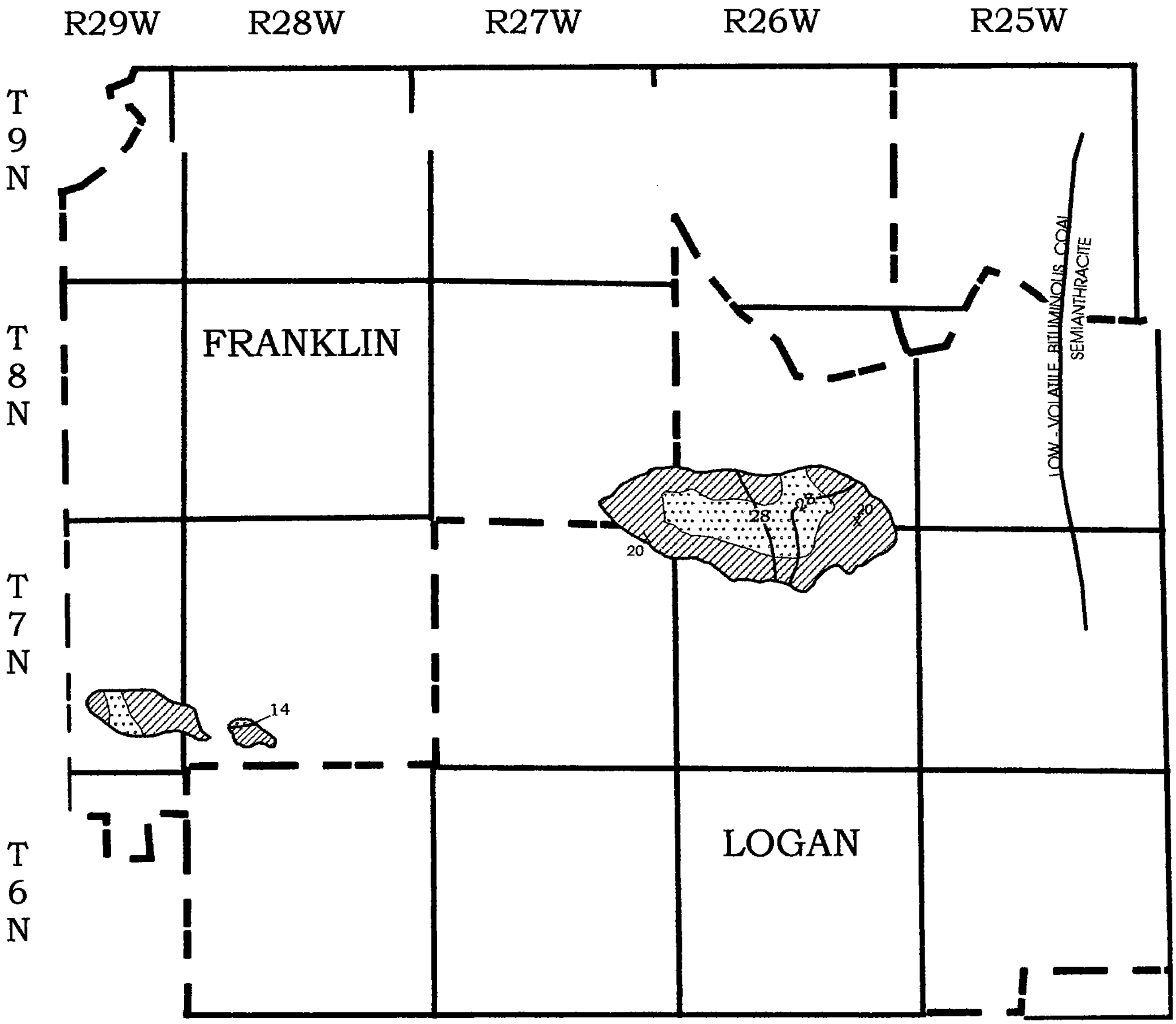
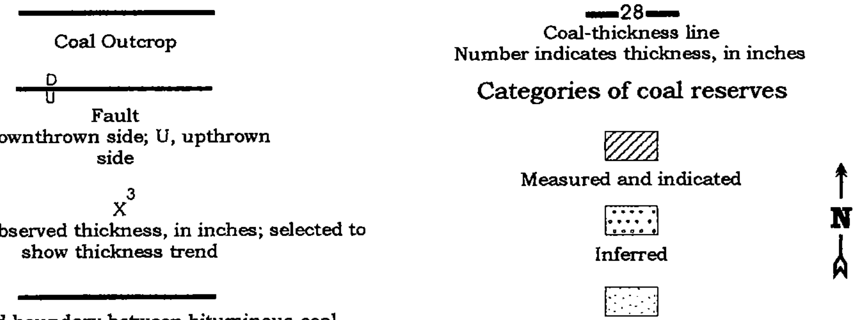


Figure 8-B

PARIS COAL BED

Geology by B. R. Haley, 1960
Digital compilation by Jerry Clark

EXPLANATION



Coal Outcrop

Fault
D, downthrown side; U, upthrown side

Reported or observed thickness, in inches; selected to show thickness trend

Generalized boundary between bituminous coal and semianthracite
Fixed-carbon content, 86 percent

Coal-thickness line
Number indicates thickness, in inches

Categories of coal reserves

Measured and indicated

Inferred

Coal less than 14 inches thick, or data insufficient to estimate reserves

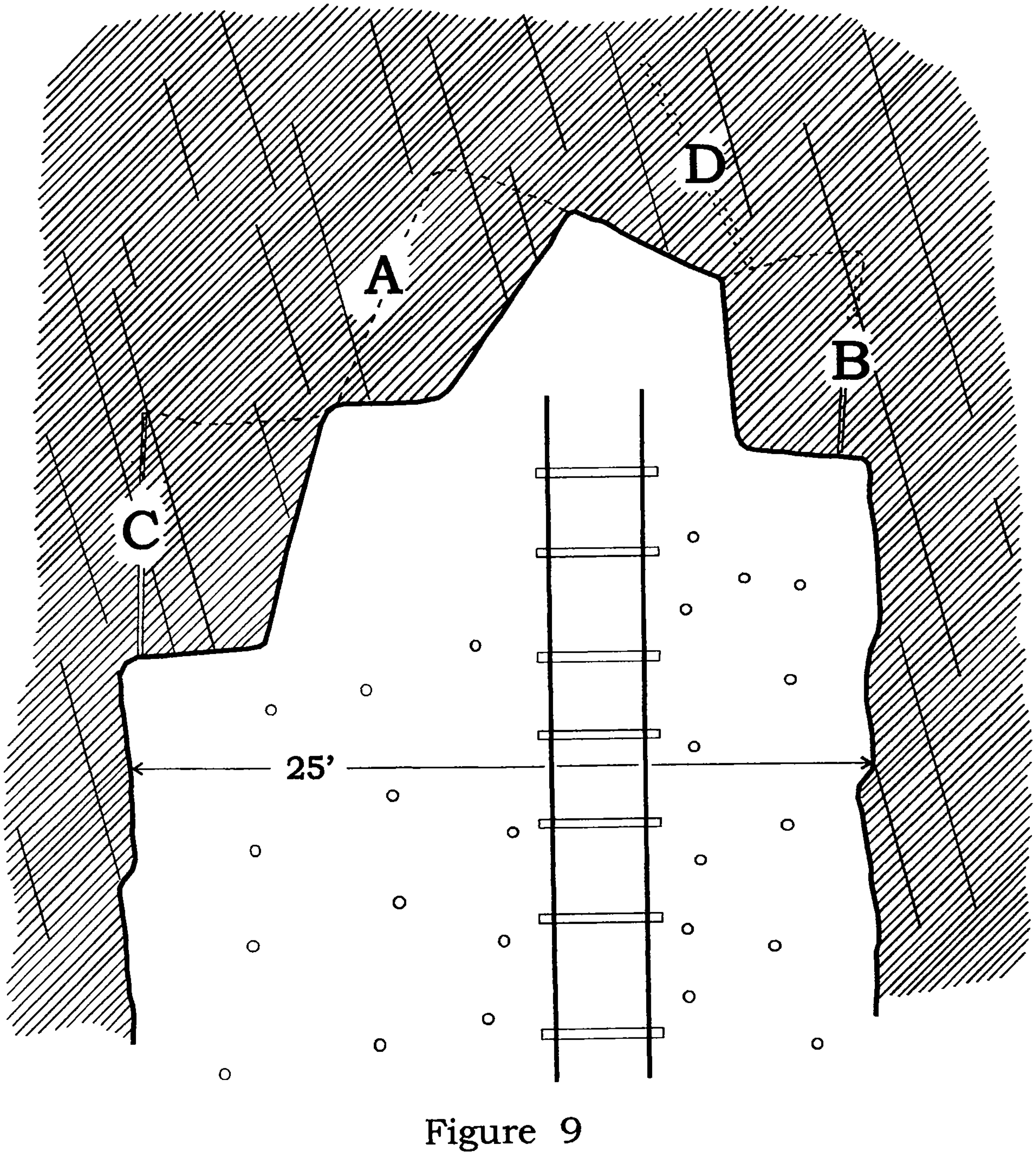


Figure 9

Plan of the face of a room, showing careless method of placing slots parallel to the slips (cleating) to throw coal towards the track in the center of the room.
(Steel, 1910, Fig. 24)

Digital compilation by Jerry Clark

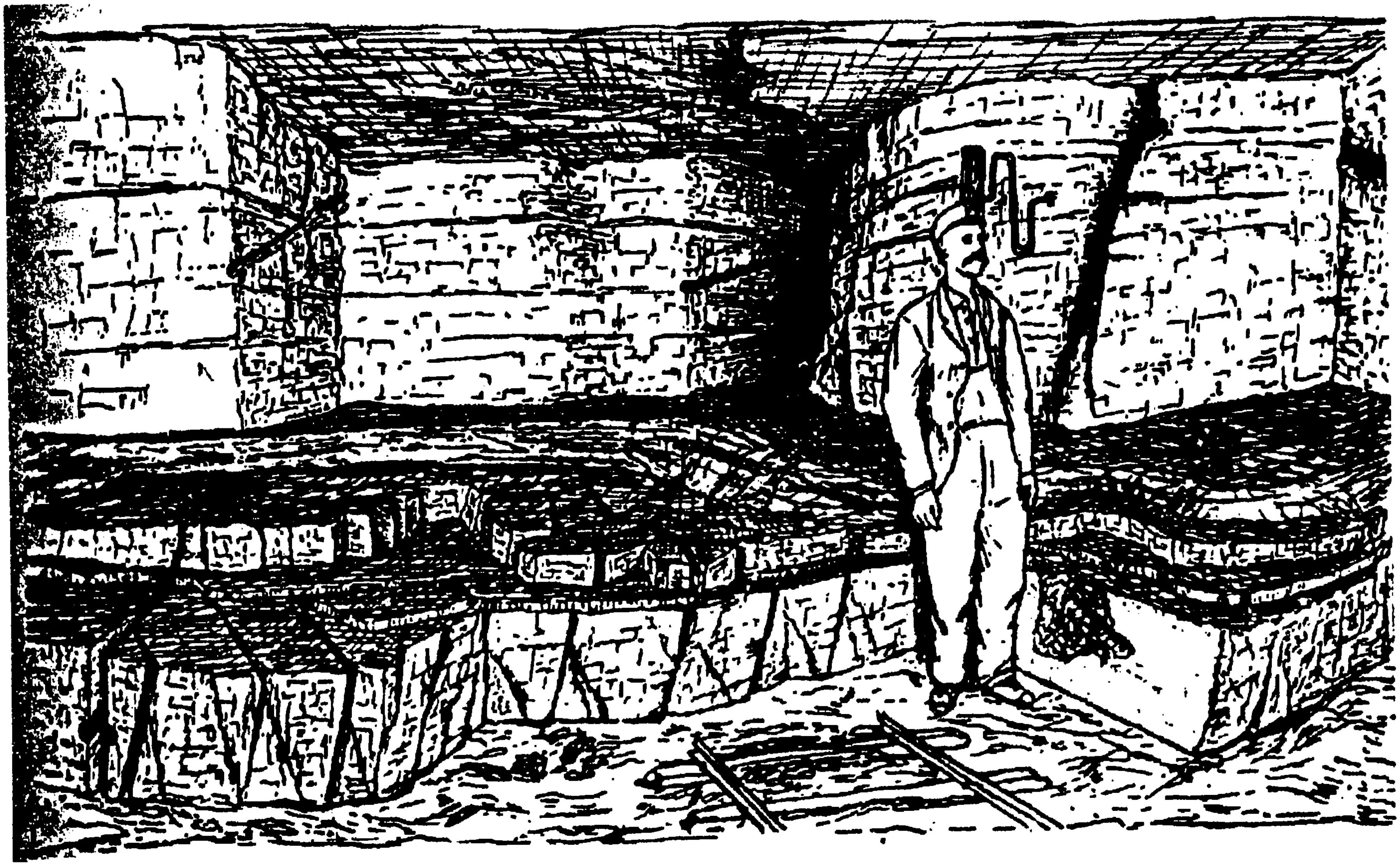


Figure 10

Ideal view of the method of working rooms at Huntington to produce the cleanest coal. Notice the cleating along the lower bed of coal. (Steel, 1910, Fig. 31)

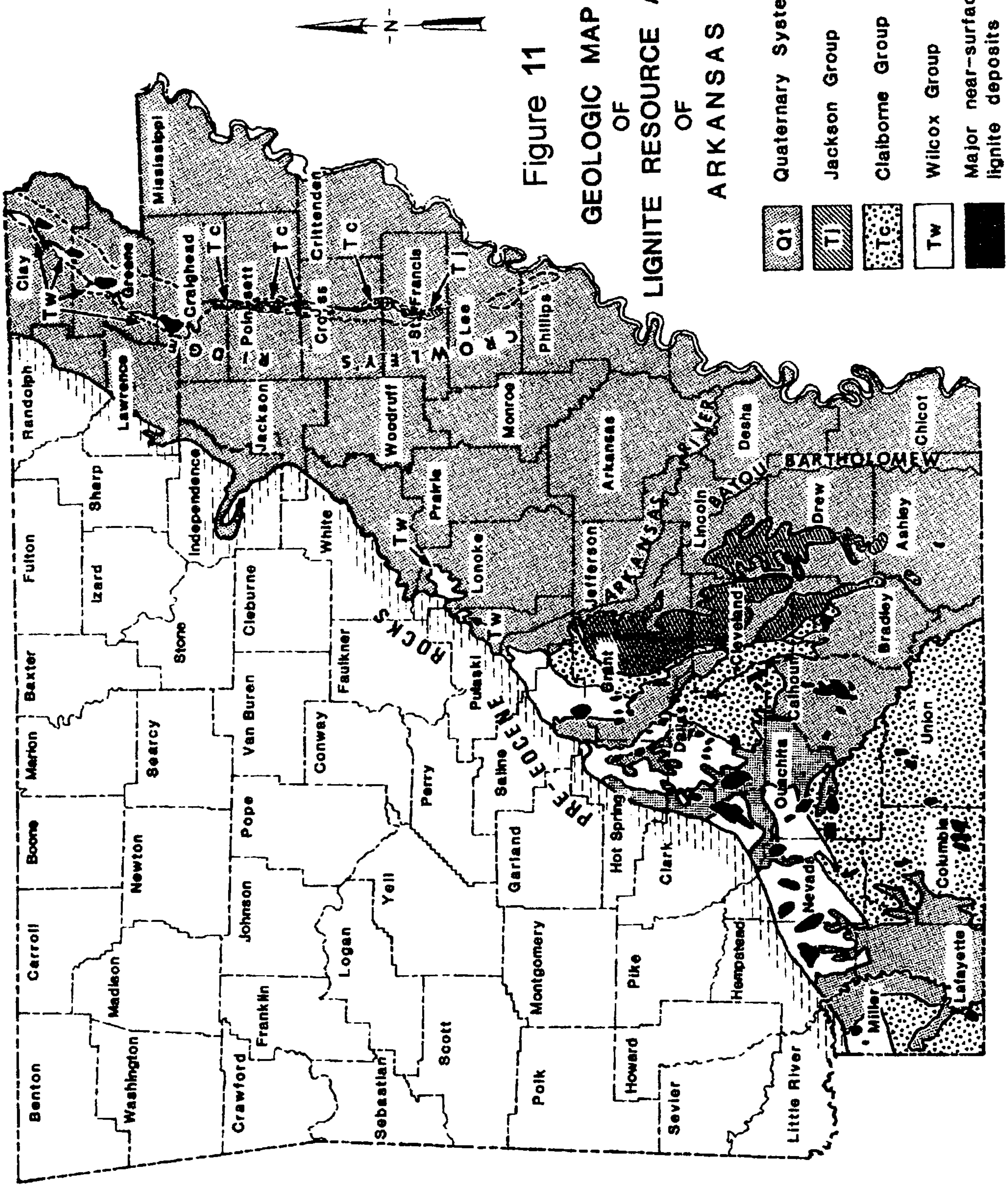


Figure 11
GEOLOGIC MAP
OF
LIGNITE RESOURCE AREA
OF
ARKANSAS

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

4

Coal stratigraphy of the northeast Oklahoma shelf area, with an overview of Arkoma basin coal geology

LeRoy A. Hemish
Oklahoma Geological Survey
Norman, OK

Hemish, L.A., 2001, Coal stratigraphy of the northeast Oklahoma shelf area, with an overview of Arkoma basin coal geology, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 72-92.

COAL STRATIGRAPHY OF THE NORTHEAST OKLAHOMA SHELF AREA , WITH AN OVERVIEW OF ARKOMA BASIN COAL GEOLOGY

LeRoy A. Hemish, Oklahoma Geological Survey

INTRODUCTION

Studies of the coal geology of the northern part of the northeast Oklahoma shelf area were carried out by the author, mostly during the late 1970s and early 1980s. The objective of these studies was to evaluate the coal resources and reserves of the northeast Oklahoma shelf area that are available for surface mining. Reports of the studies were published by the Oklahoma Geological Survey (OGS) (Hemish, 1986; 1989a; 1990). The shelf-area part of this report focuses mainly on the coal stratigraphy from those earlier reports in Craig, Nowata, Rogers, Mayes, Tulsa, Wagoner, and Washington Counties. The data were compiled from 2,000 drill and core logs, provided mostly by coal companies, and from 247 sections measured by the author. These were supplemented by other measured sections from earlier studies.

The study area comprises about 1,800 mi^2 situated in the northern part of the coal belt of eastern Oklahoma (Fig. 1). The coal-producing area of the six counties lies mostly within the Claremore Cuesta Plains geomorphic province. The region is characterized by resistant sandstones and limestones that dip gently westward and northwestward, forming cuestas between broad shale plains. Because of the low dip of the beds, the northeast Oklahoma shelf area is particularly amenable to strip mining.

Also included in this report are excerpts from an upcoming OGS publication dealing with surface to subsurface correlation of methane-producing coals in an area extending from T. 20 N. to T. 29 N., and R. 10 E. to R. 17 E. The area encompasses more than 2,700 mi^2 in Nowata and Washington Counties, and parts of Craig, Osage, Rogers, and Tulsa Counties.

An overview of the coal geology of the Arkoma basin, based largely on field investigations by Hendricks and others (1939), Trumbull (1957), Friedman (1974;1982), and Hemish (1988b; 1994a,b; 1999) supplements the main body of this report.

GEOLOGY

Northern Part of the Northeast Oklahoma Shelf Area

The six-county study area lies around the western edge of the Ozark uplift (Fig. 1). Strata dip very gently westward and northwestward at ~1°. Major deformation in the region occurred during Middle Pennsylvanian time; folds and faults associated with the deformation are of early Desmoinesian age (Huffman, 1958, p. 89). Small- and intermediate-scale anticlines and synclines, and minor faults observed in surface coal mines in the area are manifestations of the deformation.

Rose diagrams were constructed from 37 Brunton-compass measurements of cleat direction in the Craig and Nowata Counties coal field (Fig. 2A); from 20 measurements in Rogers and Mayes Counties (Fig. 2B); and from 28 measurements in Tulsa and Wagoner Counties (Fig. 2C). Weighted averages of the 85 combined measurements show that the face cleats strike N47°W, and the butt cleats strike N49°E.

Stratigraphy

General Statement

All of the minable coal horizons in the area studied are in rocks of Desmoinesian (Middle Pennsylvanian) geologic age. These rocks consist mostly of sandstone, siltstone, limestone, and shale. Coal constitutes a minor percentage of the whole.

The names of the various stratigraphic units and the types of rocks included are shown in Figure 3. Thirty-four named coal beds and several unnamed coal beds are present in the northeast Oklahoma shelf area. Many of the coals were named either in Kansas or Missouri, particularly those that have any real economic potential at this time. Hemish (1987) presented a compendium of coal nomenclature in which he discussed the origin of the coal names and identified their stratigraphic position in relation to associated markers. The coal beds themselves are excellent markers, and coalbed nomenclature is very useful in stratigraphic work.

The coal beds are separated by marine and nonmarine strata, indicating that they were laid down under cyclical conditions. According to Heckel (1991) vegetation which subsequently formed coal grew in coastal swamps near epeiric seas that covered northeastern Oklahoma during Desmoinesian time. Fluctuations of sea level caused oscillatory transgressions and regressions of the sea over the area. Channel sandstones, black shales, and interchannel coals here represent environments associated with deltas. Just as the shoreline oscillated back and forth, so did the delta environment. This accounts for the distribution, geometry, and relationships of the various rock units preserved across the area. Burial of these sediments resulted in alteration of vegetal matter to coal. Differential compaction of coals, shales, and sandstones account for much of the pinch-out and minor structures in the area.

Nine coal beds that have the requisite thickness for surface mining are present in the northern part of the shelf area of northeast Oklahoma. From oldest (lowest) to youngest (highest) they are: Rowe coal, Drywood coal, Bluejacket coal, Weir-Pittsburg coal, Mineral coal, Fleming coal, Croweburg coal, Iron Post coal, and Dawson coal (Fig. 3). Seven of these beds produce coalbed methane in the northeast Oklahoma shelf area. There are 299 completions in the Rowe; 1 in the Drywood; 13 in the Bluejacket; 18 in the Weir-Pittsburg; 21 in the Croweburg; 36 in the Iron Post; and 12 in the Dawson (B. J. Cardott, personal communication). Additionally, gas is produced from three coal beds that are of no commercial importance for surface mining in Oklahoma. They are the Riverton (15 wells), the Bevier (11 wells), and the Mulky (315 wells). Methane is also being produced from one unidentified coal bed, for a total of 742 completions in the shelf area (B. J. Cardott, personal communication, August 28, 2001). Reported gas production from the Mulky coal is enigmatic. Hemish (1986, p. 18) reported occurrence of the Mulky in Oklahoma in only three drill holes in secs. 13 and 22, T. 23 N., R. 19 E., northern Craig County, where its maximum thickness is 10 inches. Occurrence of the Mulky coal down dip to the west in Nowata, Washington, and Osage counties has not been verified by the OGS from coring. It seems probable that the methane is being produced from the Excello black shale. If present, the Mulky occurs at the base of the Excello Shale (Hemish, 1986, fig. 4).

Krebs Group

The Krebs Group is the oldest group that includes coal-bearing rocks in the study area (Fig. 3). The Krebs Group has been subdivided into four formations, the Hartshorne Formation, the McAlester Formation, the Savanna Formation, and the Boggy Formation. Thin and discontinuous coals are present in the shelf area in the oldest two formations in the Krebs Group, but they have no importance for surface mining.

Two commercially important named coals and several thin, discontinuous unnamed coals are present in the Savanna Formation. The Rowe coal, which occurs near the middle of the Savanna (Fig. 3) is stratigraphically the lowest coal having surface-mining value in the study area. It has been mined chiefly in the area southeast of the town of Inola in the extreme southern part of Rogers County, where it ranges from 10 to 30 inches in thickness at a depth of <100 ft. It thins to the north, and in Craig County it has limited economic promise only in small areas. The outcrop line of the Rowe coal is shown in Figure 4.

The other commercial coal in the Savanna Formation is the Drywood coal, which occurs near the top of the formation (Fig. 3), just below the Bluejacket Sandstone. The Drywood has been mined in past years in Craig County in sec. 13, T. 26 N., R. 19 E., where it was measured at 3 feet in thickness. The thickness of the Drywood coal varies, and along most of its outcrop boundary (Fig. 5) it is not of mineable thickness. Core-drilling in northeastern Craig County shows that in some places channels that were filled by the Bluejacket Sandstone have cut into or completely through the Drywood coal (Hemish, 1989b, fig. 5).

The Boggy Formation is the youngest formation in the Krebs Group. It contains only one coal bed having commercial value in the study area--the Bluejacket coal (Fig. 3), which occurs above the Bluejacket Sandstone and below the Inola Limestone. The Bluejacket coal is absent throughout all of Craig County except for a small area in the extreme southwestern corner. The Bluejacket bed is of mineable thickness in eastern Rogers County and west-central Mayes County in T. 22 N., Rs. 17 and 18 E., where it ranges from 10 to 18 inches in thickness. Although the bed has not been mined in recent years, past underground mining is evidenced by several abandoned, caved-in drift openings in sec. 16, T. 22 N., R. 18 E. The outcrop line of the Bluejacket coal is shown in Figure 6.

Cabaniss Group

The Cabaniss Group is represented by only the Senora Formation on the platform area of northeastern Oklahoma (Branson and others, 1965, p. 34). It includes the strata between the base of the Weir-Pittsburg coal and the base of the Fort Scott Formation (Fig. 3). Ten named coal beds are present in the Senora Formation, of which five are economically important for surface mining. Three of the other five beds--the Bevier, the Mulky, and the Scammon (tentatively identified)--are too thin to be mined in Oklahoma but are mined in Kansas and Missouri. The RC bed is also too thin to be mined and is known to be present only in Rogers and Wagoner Counties (Hemish, 1989a, 1990). The Tebo has limited economic value and in Oklahoma is thick enough for surface mining in only Wagoner and Muskogee Counties.

The oldest commercial coal in the Senora Formation is the Weir-Pittsburg. It crops out in a diagonal line from northeast to southwest across Craig County but is unmappable in southern Rogers County (Fig. 4). It is the thickest coal bed occurring in the study area, with reported thicknesses ranging from 1.5 feet to 2.0 feet in northeastern Rogers County and northwestern Mayes County. It has a recorded maximum thickness of 6.2 feet at a depth of more than 400 feet in northwestern Craig County in T. 29 N., R. 18 E. The Weir-Pittsburg has been mined extensively in the past west of Welch, in Craig County, and in more recent times near Estella, also in Craig County, and around the town of Chelsea in northeastern Rogers County and northwestern Mayes County.

The Mineral coal (Fig. 3) occurs stratigraphically above the Chelsea Sandstone, and, in northern Craig County, below the Russell Creek Limestone. In Rogers County exposures of the Mineral coal are difficult to find, but reported thicknesses in the county vary from 6 inches to more than 2 feet. West of Chelsea, in Rogers County, the Mineral coal is from 1 to 1.5 feet thick and has been mined by Peabody Coal Company in past years. The Mineral was mined in the late 1970s in northern Craig County where it reaches its maximum thickness of 27 inches. Typically, it is 14 to 18 inches thick in that area. The outcrop line of the Mineral coal is shown in Figure 6.

The Fleming coal is present in Oklahoma only in the northern one-third of Craig County (Fig. 6). The Fleming is extremely variable in thickness. It locally attains thicknesses of 18 inches but tends to thin abruptly within a short distance. Its stratigraphic position is approximately midway between the underlying Mineral coal and the overlying Croweburg coal (Fig. 3); therefore, the Fleming coal is sometimes mined with one or the other, or with both.

The Croweburg coal crops out in a nearly continuous line extending diagonally from northeast to southwest through the middle of Craig County, the southeast corner of Nowata County, and the middle of Rogers County (Fig. 5). It averages about 18 inches in thickness and has long been prized for its high quality. The Croweburg has been extensively strip mined along the outcrop belt throughout Craig, Nowata, and Rogers Counties, often to depths as great as 60 to 70 feet.

The Croweburg coal is readily identified in the field by the overlying succession of beds (Fig. 3). It is directly overlain by light-gray silty shale that varies in thickness from as much as 50 feet in Nowata County and northern Rogers County, to about 30 feet in southern Rogers County, and to about 10 feet in northern Craig County. The light-gray shale is overlain by black, fissile shale containing phosphatic nodules (Oakley Shale). The black shale is overlain in turn by the Verdigris Limestone, a persistent, dark-gray fossiliferous limestone, about 2 to 8 feet thick, that weathers yellow-brown.

The Iron Post coal is the uppermost commercial coal in the Senora Formation. It crops out across Craig, Nowata, and Rogers Counties in an irregular line roughly parallel to the outcrop line of the Croweburg coal (Fig. 4). The Iron Post coal lies about 30 to 50 feet above the Verdigris Limestone and is overlain by a few inches to a few feet of gray and/or black shale containing phosphatic nodules (Kinnison Shale). The shale is overlain in turn by an impure, dense, fossiliferous brown-weathering limestone, 2 to 10 feet thick, known as the Breezy Hill. Another black, phosphatic shale, 4 to 8 ft. thick (Excello Shale), separates the Breezy Hill Limestone from the base of the Blackjack Creek Limestone, the lowermost unit of the Marmaton Group. If present, the Mulky coal occurs at the base of the Excello Shale.

Marmaton Group

The Marmaton Group overlies the Cabaniss Group and is at the top of the Desmoinesian Series (Fig. 3). Only one coal of economic importance is present in the Marmaton Group in the study area--the Dawson coal, which crops out in western and north-central Tulsa County, northwestern Rogers County, and central Nowata County (Fig. 5). Its maximum known thickness is 30 inches.

Depositional Environments

Operators who work in the northeastern Oklahoma shelf area frequently find the task of identifying methane-producing coal beds frustrating. Examination of existing logs and careful research of available literature do not always provide the answers. Why?

To find the answers one must go back through geologic time and revisit the depositional environment. As discussed previously, epeiric seas periodically covered much of a large land mass that is now the Midcontinent of the United States. About 60 cycles of glacial-eustatic marine transgression and regression were recognized in the mid-Desmoinesian to mid-Virgilian along the Midcontinent outcrop belt (Heckel, 1989, p. 160). Differences in water depth during high stands, in the position of the shoreline during lowstands, in the encroachment of detrital clastics during regression, and in the thickness of the limestone facies formed at intermediate stands resulted in variations in the basic sequence of lithologic units. Stratigraphic patterns that resulted from periodic waxing and waning of glaciations show variable thicknesses, dependent on time. Delta shifting, which operated wherever the shoreline stood for a sufficient period of time also introduced stratigraphic sequences that interrupted the typical cyclical successions.

The typical vertical succession of lithologic units consists of 1) terrestrial blocky mudstone often capped with coal, fluvial-deltaic sandstone and shale; overlain by 2) thin transgressive marine limestone; overlain by 3) thin black phosphatic shale, deposited in deep water; overlain by 4) thicker regressive, shoaling-upward marine limestone capped by terrestrial mudstone paleosol or fluvial-deltaic clastics (Heckel, 1989, p. 162).

However, and particularly in Oklahoma, ideal successions are seldom found in the stratigraphic record. Examination of cross sections A-A' and B-B' (Hemish, 1986 pl. 6) show that shelf geology is not "layer cake". Coal beds and other markers are not always continuous. In places coals merge to form one bed; in others a bed may split to form two or more beds. In critical areas markers may be absent. Lithologic intervals between markers may be extremely variable. (A shale 20 ft. thick in one log may be 80 ft. thick in another). Sandstone channels often cut out markers and interrupt the typical cyclical succession of beds.

Surface to Subsurface Correlations

Changing depositional environments related to sea level fluctuations are the main cause of the problems facing workers attempting to make accurate interpretations of the stratigraphy in the subsurface. The only sure way to correlate beds from surface to subsurface is through close-spaced drilling. However, because of the availability of numerous existing logs in the shelf area, exploration-drilling expenses can be greatly reduced, and interpretations can be made from the existing logs with a reasonable degree of confidence. Construction of paleogeographic maps where sufficient data are available can lead to a better understanding of the distribution of coal beds in the subsurface, and hence, more accurate application of existing nomenclature.

A subsurfacae study of coal beds in a 2,700 mi^2 area in six counties in Oklahoma directly south of the Kansas state line and west of the outcrop belt has been made by the author, using existing well logs. Six cross sections were constructed from the logs to provide a reference subsurface stratigraphic framework throughout the area (Fig. 7). Sixty-two well logs (gamma ray and bulk density or neutron) were selected from >200 logs examined at the OGS Log Library. As an aid in recognizing the various coal beds that produce methane, persistent markers such as the Checkerboard Limestone, Fort Scott Limestone, Verdigris Limestone, Tiawah Limestone, and Inola Limestone were identified. Persistent black shales, such as the Excello Shale, the Oakley Shale and several unnamed shales also proved useful as markers. Two type logs were designated (one in the northern part of the study area, and one in the southern part). The northern type log is reproduced here (Fig. 8), and is representative of the logs used in the study.

Correlation of named coals from surface studies discussed previously in this paper with those identified in the subsurface study will provide a much-needed basis for proper recognition of the 10 methane-producing coals in the shelf area. Determination of coal bed thicknesses from the logs was not attempted. However, deflections in the log curves suggest that most of the beds are probably not more than 1 to 2 ft in thickness, with a few exceptions, where the coal may be as much 4 ft thick.

Arkoma basin

General Statement

The Arkoma basin is an elongate tectonic province that extends about 250 mi across parts of eastern Oklahoma (Fig. 1) and west-central Arkansas. The Arkoma basin is bounded on the south by the Ouachita Mountains, on the southwest by the Arbuckle Mountains, on the north by the Ozark uplift, and it grades northwestward into the northeast Oklahoma shelf area. The Arkoma basin is characterized by a great thickness of sedimentary rocks: about 5,000-20,000 ft (Johnson, 1988, p.1). The coal-bearing strata in the basin are in the early Desmoinesian Krebs Group and the overlying Cabaniss Group (Fig. 9). These rocks were deposited during major subsidence of the Arkoma basin before initial folding of strata in the basin.

There are marked differences in the coal-bearing strata between the Arkoma basin and the northeast Oklahoma shelf area. The main differences between the two areas are: 1) Coal-bearing rocks present above the Senora Formation in the shelf area are absent in the Arkoma basin; 2) Stratigraphic units are generally much thicker in the Arkoma basin; 3) Commercial coal beds in the northern shelf area pinch out to the south and are absent in the basin; conversely, certain well-developed commercial coals in the Arkoma basin, such as the Hartshorne coal, pinch out to the north, or have no commercial value in the shelf area, owing to thinness; 4) Quality of the same coal in the two regions often varies because of different depositional environments (Hemish, 1988b, p. 7). Additionally, strata in the Arkoma basin are much more deformed than they are in the shelf area. Beds have been folded into broad, northeast-trending synclines and narrow anticlines, resulting in steep dips of the beds in some areas (Trumbull, 1957, p. 339; Friedman, 1974, p. 6). Faulting is also common throughout the Arkoma basin.

Stratigraphy

All of the minable coals in the Arkoma basin are in rocks of Desmoinesian age. They are in the Hartshorne, McAlester, Savanna, and Boggy Formations of the Krebs Group, and, in the extreme northwestern part of the basin, in the Senora Formation of the Cabaniss Group. Figure 9 is a generalized stratigraphic column showing the relative positions of the coal beds in the Arkoma basin. As in the shelf area, the coal beds are separated by marine and nonmarine strata, indicating cyclical conditions during deposition. The rocks consist mostly of shale, sandstone, and siltstone, with limestone and coal a minor percentage of the whole. Only the coal beds that produce methane, or may have methane-producing potential are briefly discussed below.

Krebs Group

The Lower Hartshorne coal is stratigraphically the lowest coal bed in the Krebs Group. It occurs in the upper part of the Hartshorne Formation, and ranges in thickness from 0.7 to 7.0 ft (Fig. 9) (Hemish and Suneson, 1997). It is one of the favorite targets for coalbed methane production in the basin.

The Upper Hartshorne coal occurs in the Hartshorne Formation a few inches to as much as 180 ft above the Lower Hartshorne coal (Trumbull, 1957, p. 345). It marks the boundary between the Hartshorne Formation and the overlying McAlester Formation (in Oklahoma). The Upper Hartshorne coal ranges from 0.2 ft to 4.5 ft thick (Fig. 9). In parts of Haskell, and Le Flore Counties the Upper and Lower Hartshorne beds coalesce or are separated by only a few inches or a few feet of bony coal or coaly shale (Trumbull, 1957, p. 345). Due to the convergence of the 6-ft-thick Lower Hartshorne coal bed and the 4-ft-thick Upper Hartshorne coal bed, a single 10-ft-thick bed of coal is exposed in the NW1/4NW1/4SW1/4NE1/4 sec. 35, T.6 N., R.18 E., Latimer County. The coal bed is called the Hartshorne coal, and it is the thickest known occurrence of coal in the State (Hemish, 1999, p. 34).

The McAlester (Stigler) coal occurs in the McAlester Formation. It ranges from 1.0 ft to 5.0 ft in thickness (Fig. 9), and is widespread throughout the Arkoma basin. It has been extensively mined on the surface as well as underground (Hendricks and others, 1939). The Upper McAlester coal was strip mined in recent times in Latimer County near Red Oak in conjunction with the McAlester coal. It ranges in thickness from 0.2 ft to 1.7 ft (Fig, 9).

The Cavanal coal occurs in about the middle of the Savanna Formation. It has commercial mining importance only in Le Flore County around Cavanal Mountain. It was shown by Friedman (1982, pl. 3) as the Lower Cavanal coal (0.2-2.2 ft thick), and the Upper Cavanal coal (1.2-3.2 ft thick) (Fig. 9). The Rowe coal occurs stratigraphically above the Cavanal coals, but has been identified only in the northern part of the Arkoma basin where it is 0.3-1.4 ft thick (Fig. 9).

The Lower Witteville occurs near the top of the Bluejacket Sandstone Member of the Boggy Formation. It was mined underground in the past in Le Flore County around Cavanal Mountain, where it is as much as 4.7 ft thick. It was traced as far north as Muskogee County, but it has no commercial value due to thinning, other than in Le Flore County (Hemish, 1994a).

The Secor coal also occurs in the Boggy Formation, stratigraphically just above the Bluejacket Sandstone (Fig. 9). It is 0.1-4.0 ft thick, and is widespread throughout the Arkoma basin. It has good potential for coalbed-methane exploitation, but thickness and quality are variable (Hemish, 1988b).

Cabaniss Group

The Croweburg (Henryetta) coal is present in the Senora Formation of the Cabaniss Group in only the extreme northwestern part of the Arkoma basin. It is 0.6-2.8 ft thick in that area (Hemish, 1994b) (Fig. 9). However, just to the northwest, in Okmulgee and Okfuskee Counties (which is technically part of the shelf area), the Croweburg coal is >3.0 ft thick over an extended area (Hemish, 1994b, pl. 3).

CONCLUSIONS

Although a greater number of coal beds have methane-producing potential in the northeast Oklahoma shelf area, they are generally thinner and less widespread than those in the Arkoma basin. It is probable that future exploration will reveal that many of the coal beds discussed above will prove to be good reservoirs in areas such as the western part of the Arkoma basin as well as the southern part of the northeast Oklahoma shelf area.

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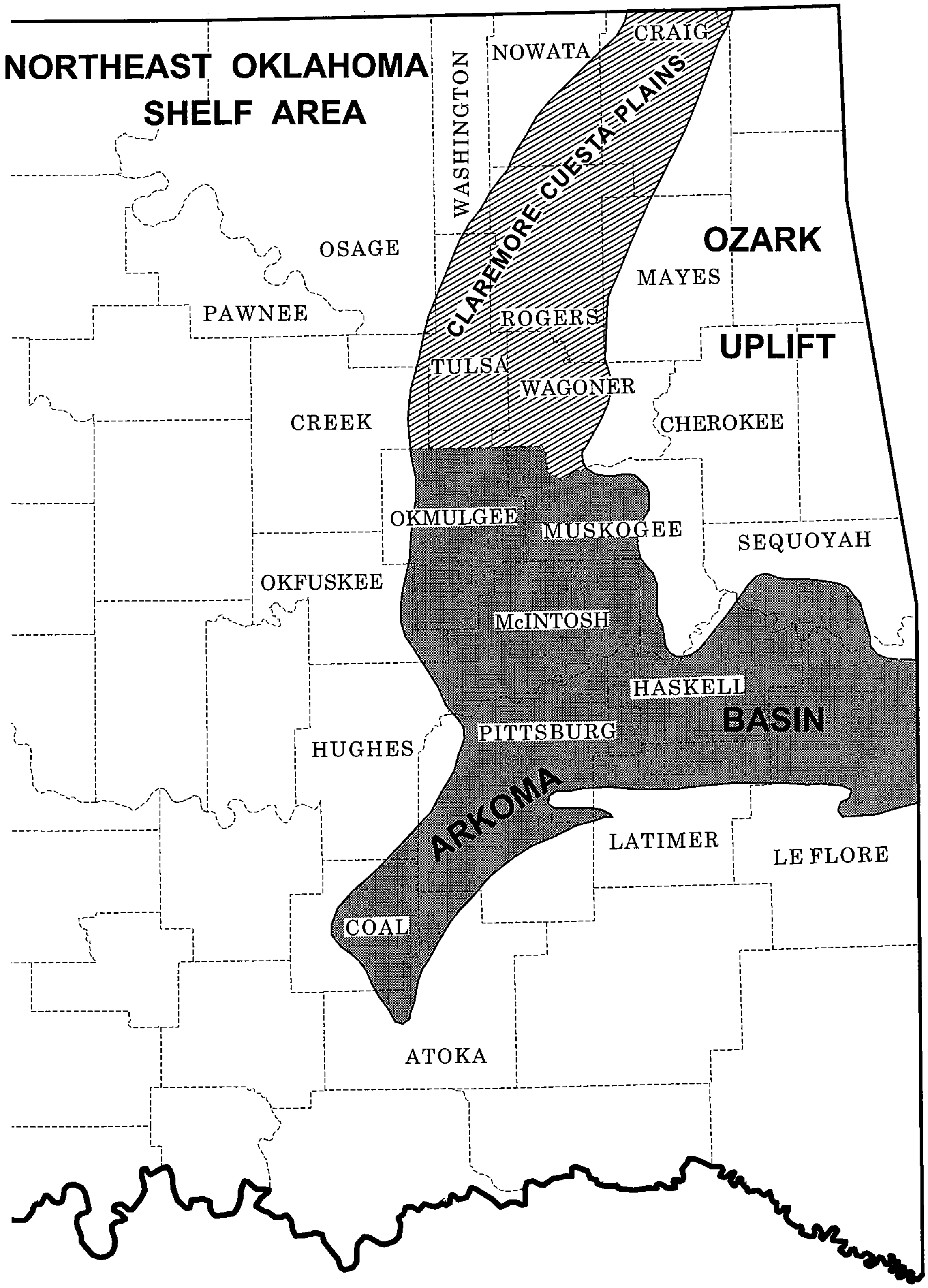

Figure 1. Index map of Oklahoma, showing the eastern Oklahoma coal field (shaded); the six-county area of this report; and the geomorphic provinces disscussed in the text.

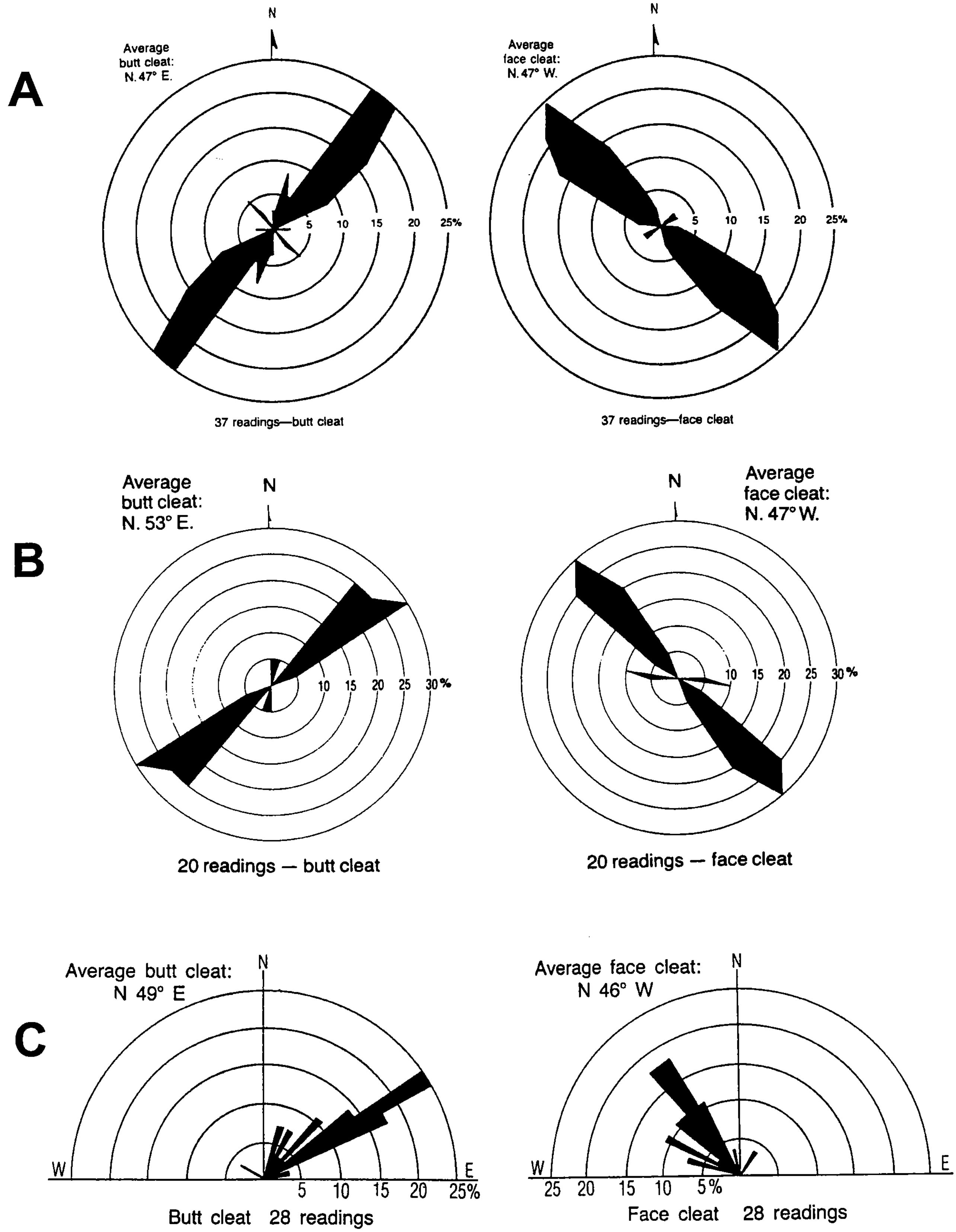

Figure 2. A-Rose diagrams of cleat orientations in coal beds of Craig and Nowata Counties (from Hemish, 1986, fig. 7, app. 4).
B-Rose diagrams of cleat orientations in coal beds of Rogers and Mayes Counties (from Hemish, 1989a, fig. 8, app. 4).
C-Rose diagrams of cleat orientations in coal beds of Tulsa and Wagoner Counties (from Hemish, 1990, fig. 8, app. 4).

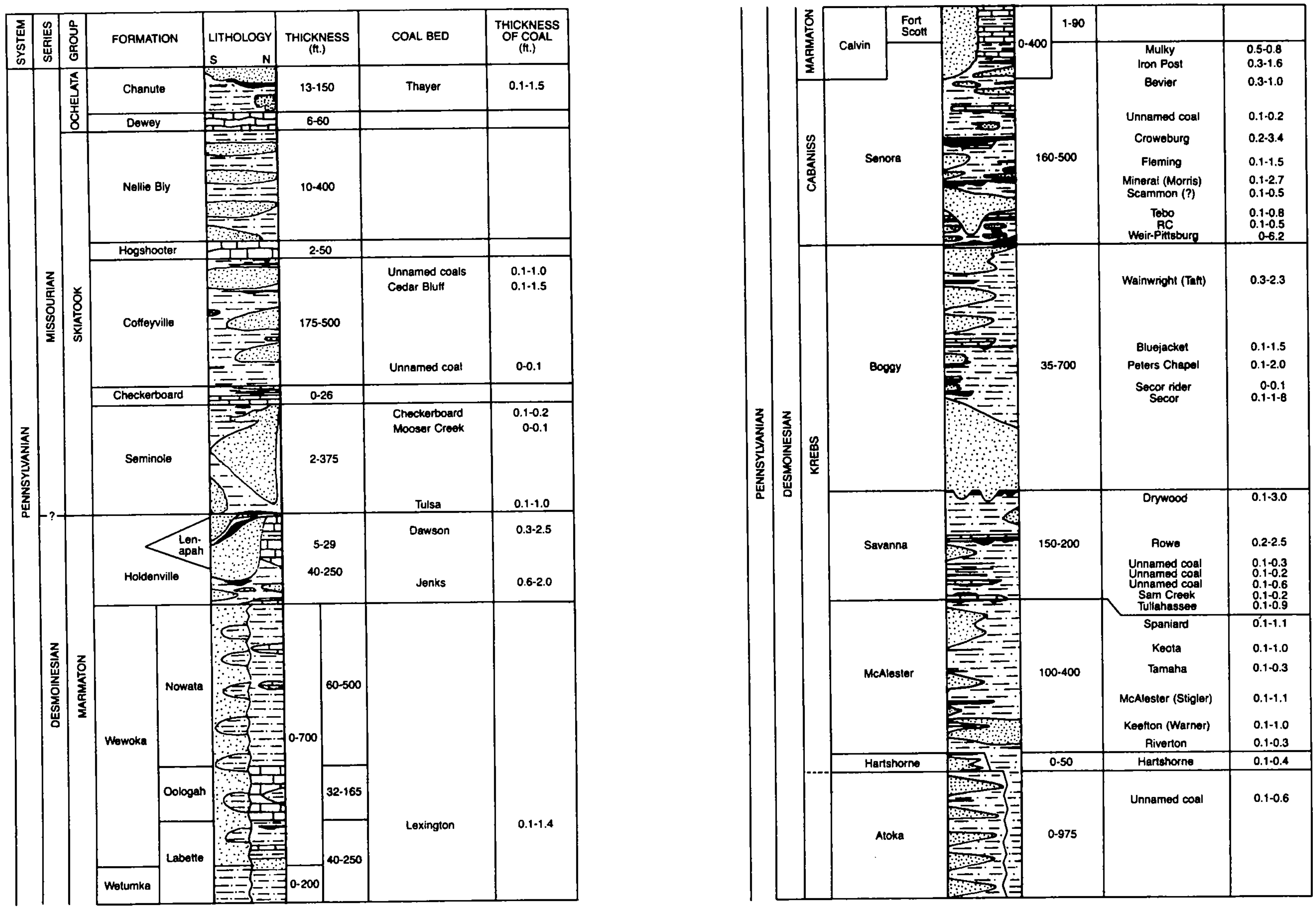

Figure 3. Generalized stratigraphic column of coal-bearing strata of the northeast Oklahoma shelf (from Hemish, 1988a, fig. 6).

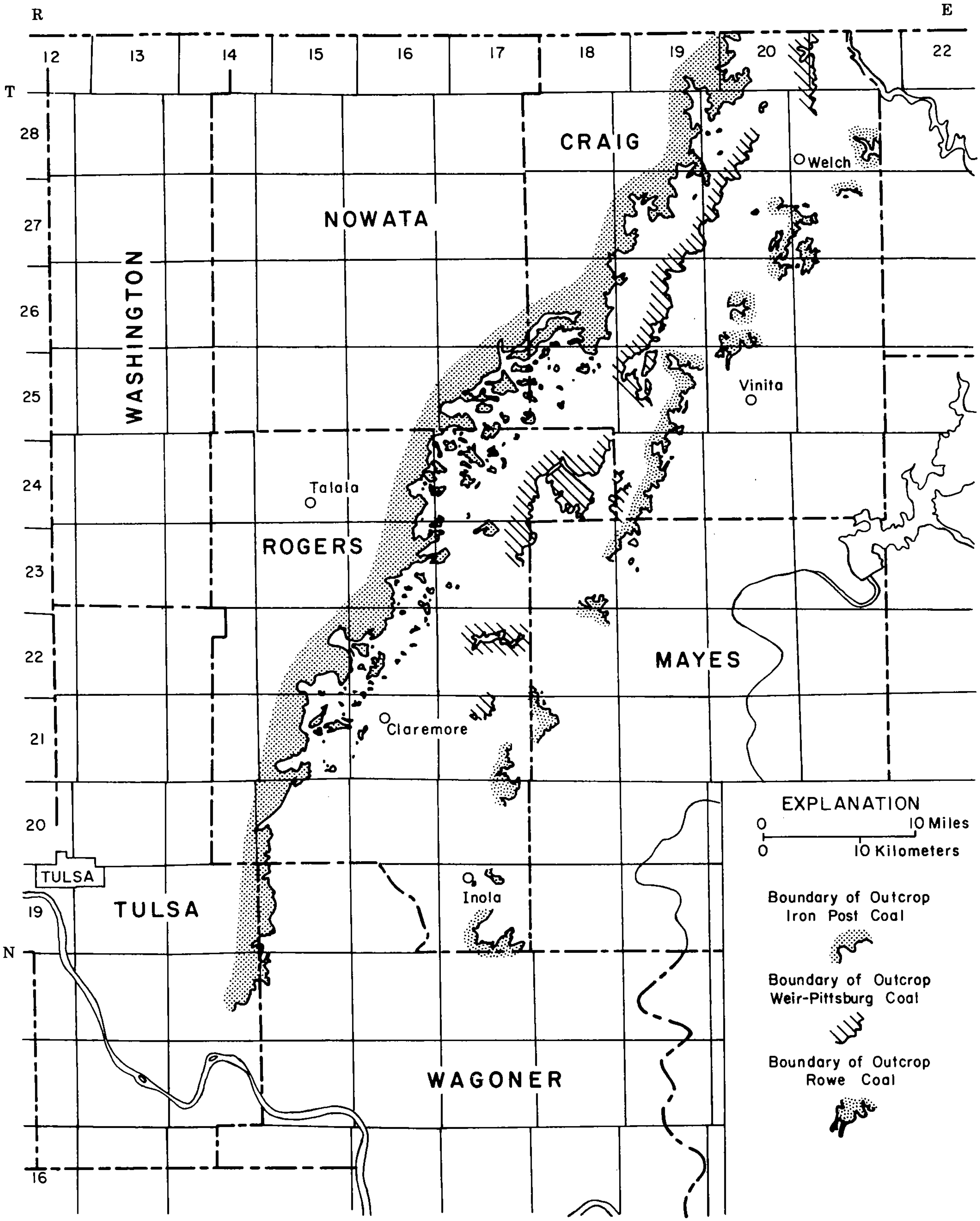

Figure 4. Coal outcrop map of the northeast Oklahoma Shelf area showing the boundary lines of the Iron Post, Weir-Pittsburg, and Rowe coal beds (from Hemish, 1984, fig. 3).

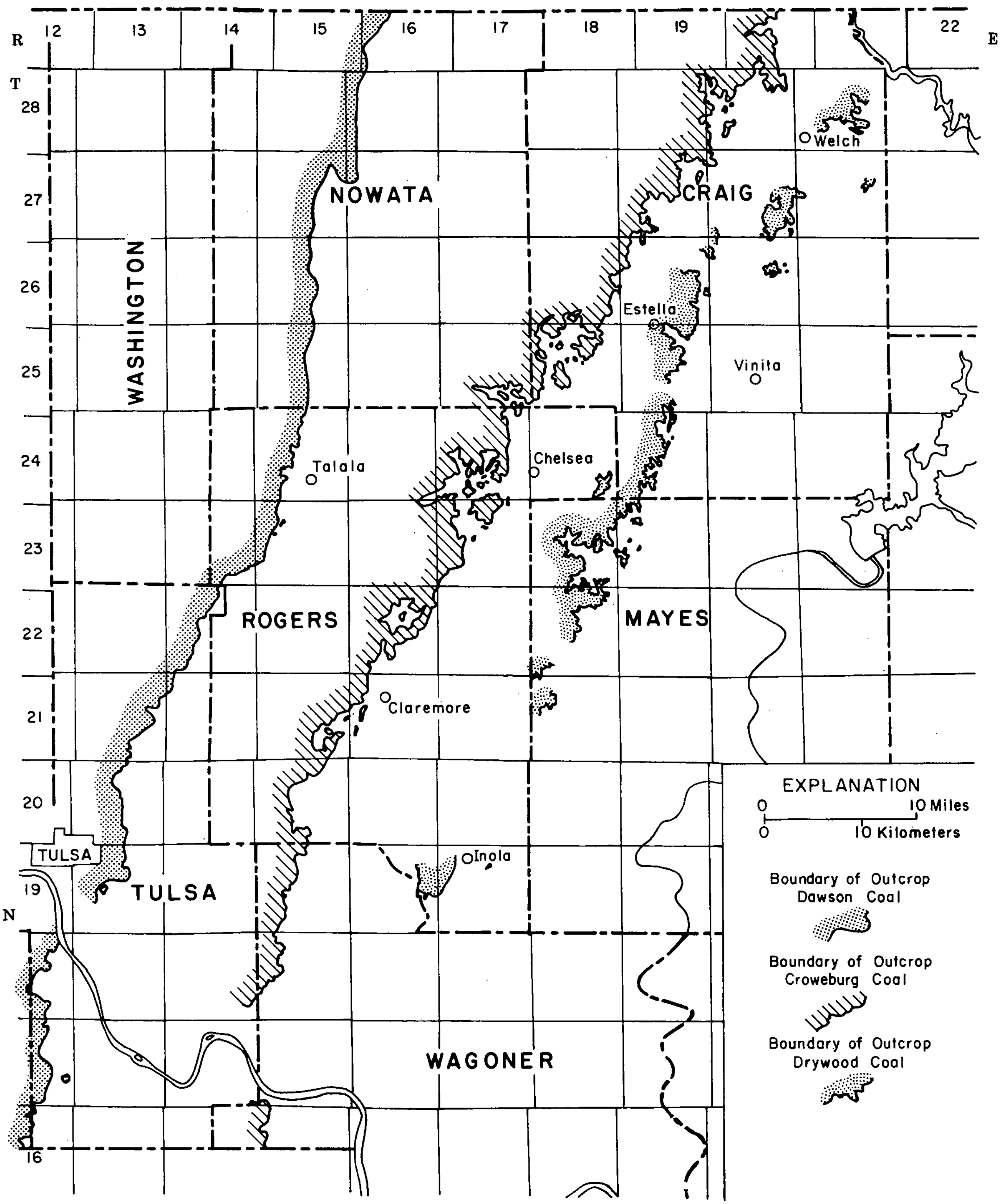

Figure 5. Coal outcrop map of northeast Oklahoma shelf area showing the boundary lines of the Dawson, Croweburg and Drywood coal beds (from Hemish, 1984, fig 2).

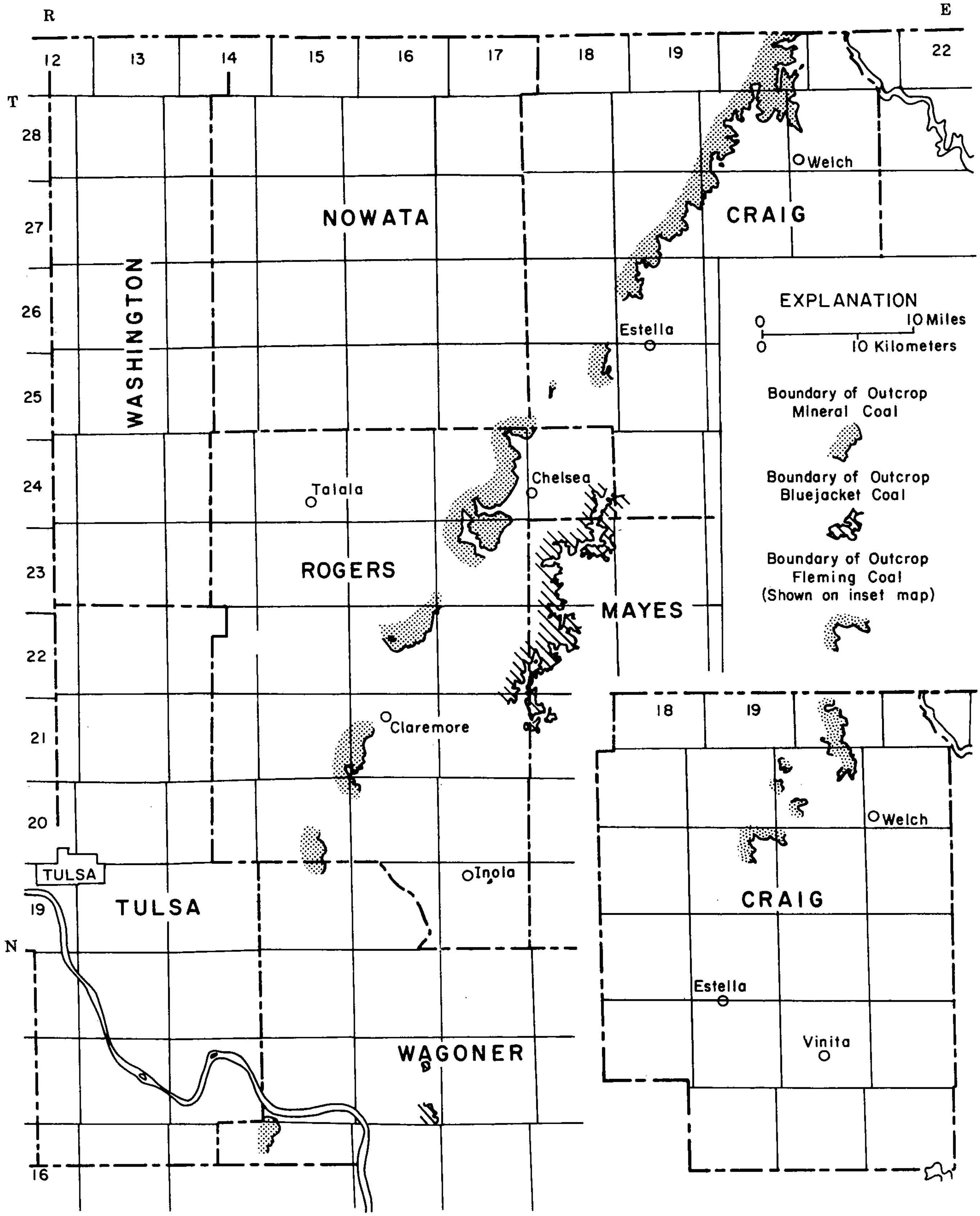

Figure 6. Coal outcrop map of northeast Oklahoma shelf area showing the boundary lines of the Fleming, Mineral, and Bluejacket coal beds (from Hemish, 1984, fig. 4).

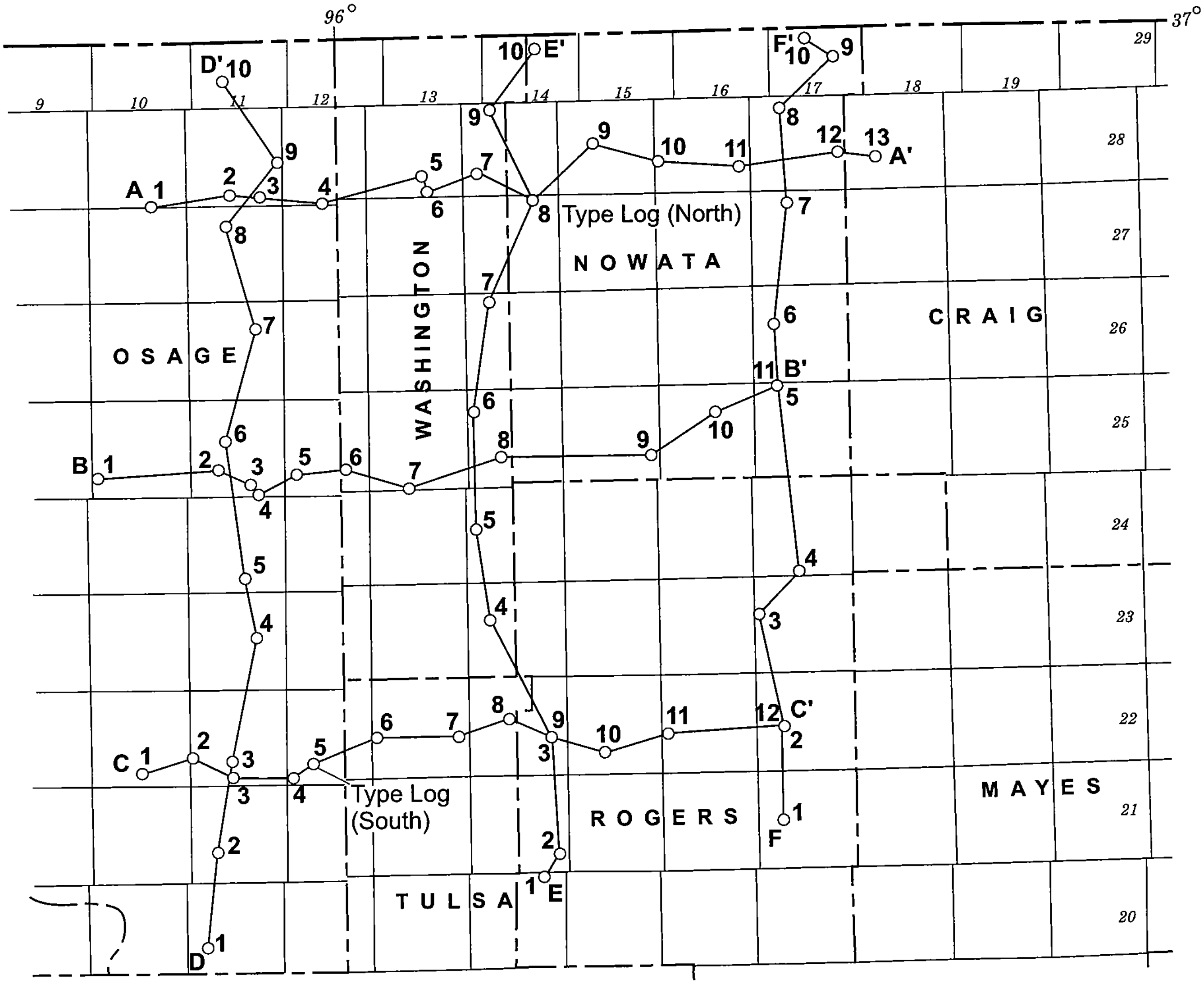

Figure 7. Index map showing location of wells and lines of cross sections for northeast Oklahoma shelf coalbed-methane subsurface study (modified from Hemish, [in preparation]).

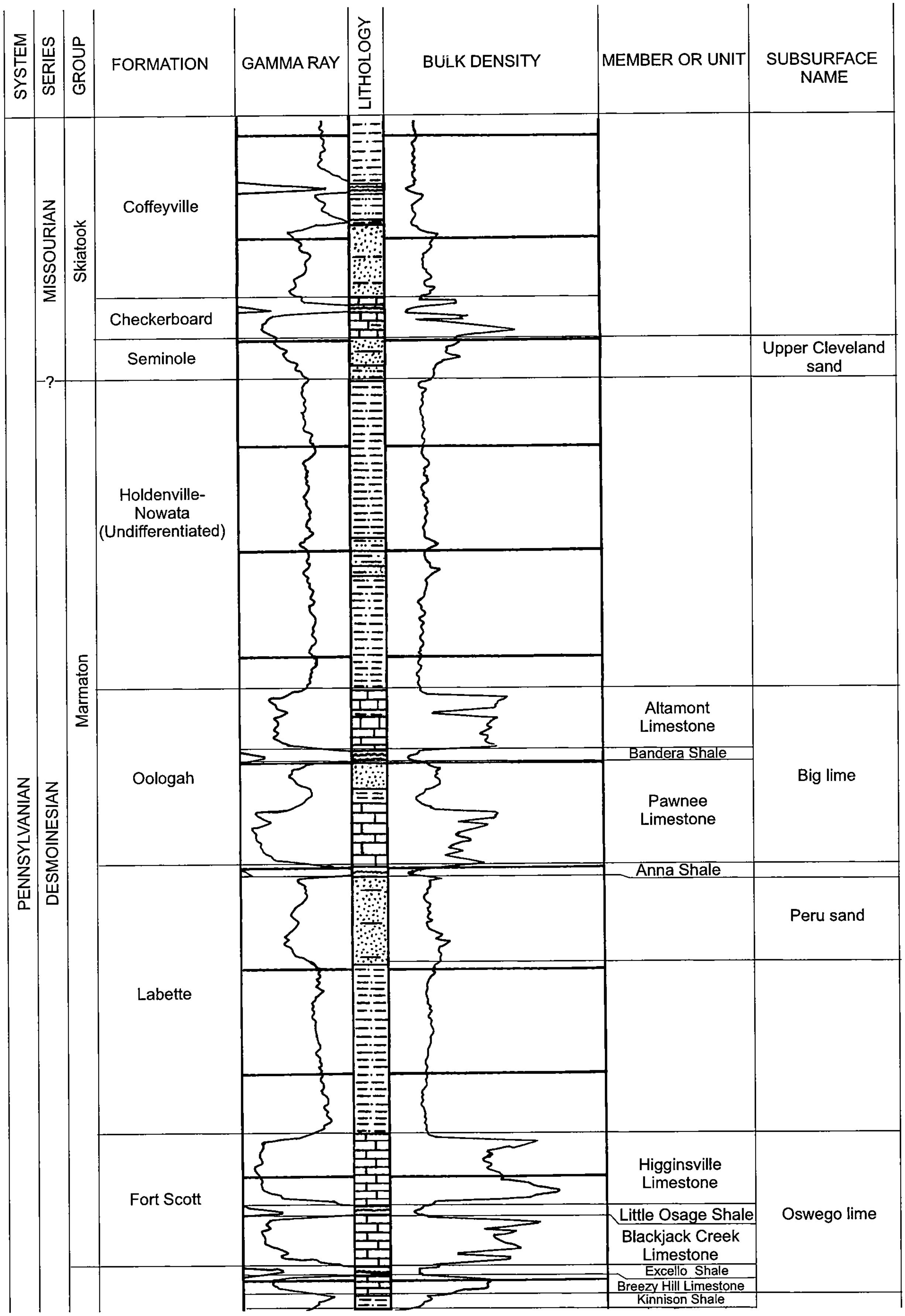

Figure 8. Type log for the northern part of the northeast Oklahoma shelf area—part of electric-log from Miracle 2 F. Lutz College well, NW¼ sec. 2, T. 27 N., R. 14E., Nowata County, Oklahoma (for map location see well E 8, Fig. 7). (From Hemish, [in preparation]).

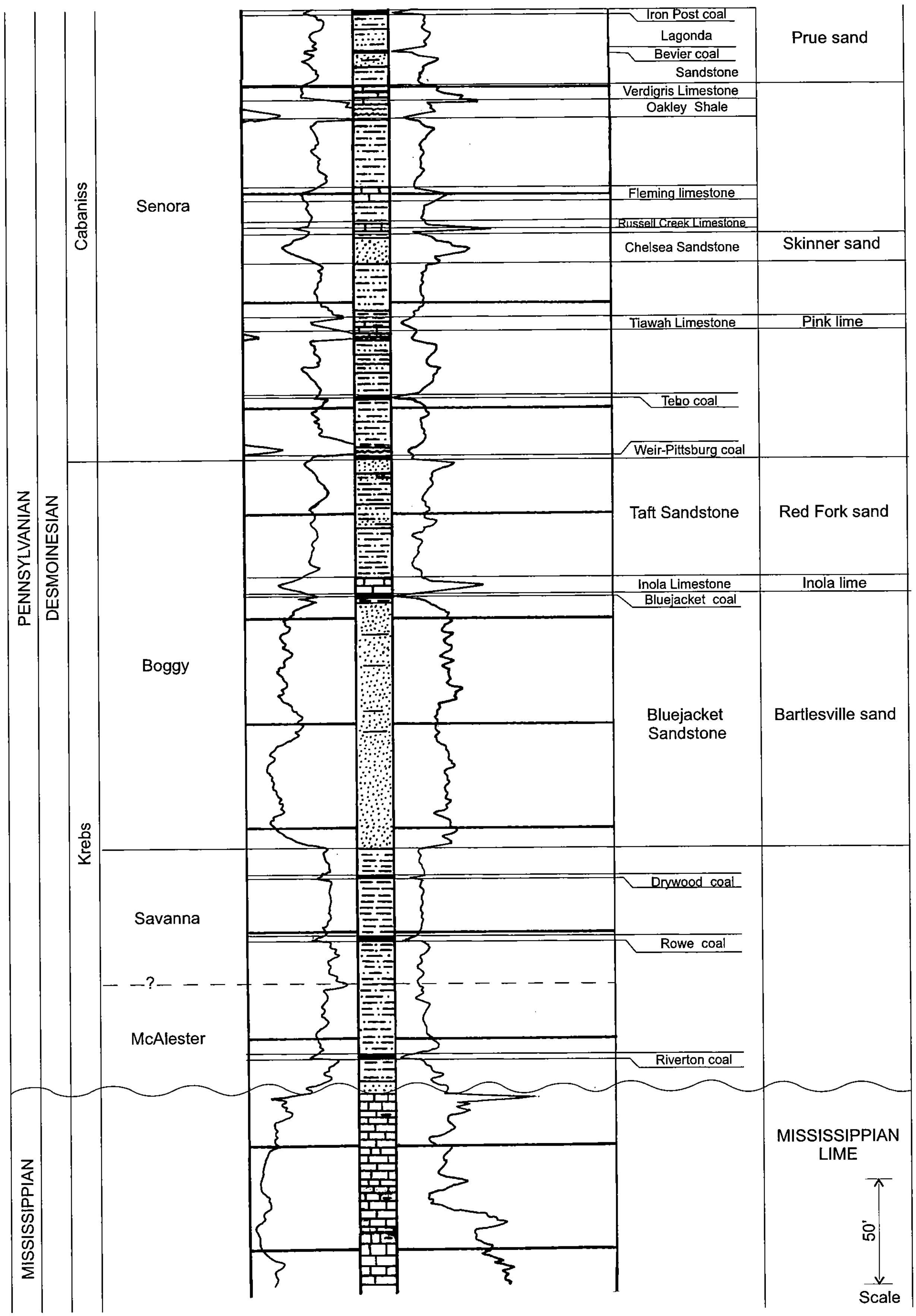

Figure 8. (Continued).

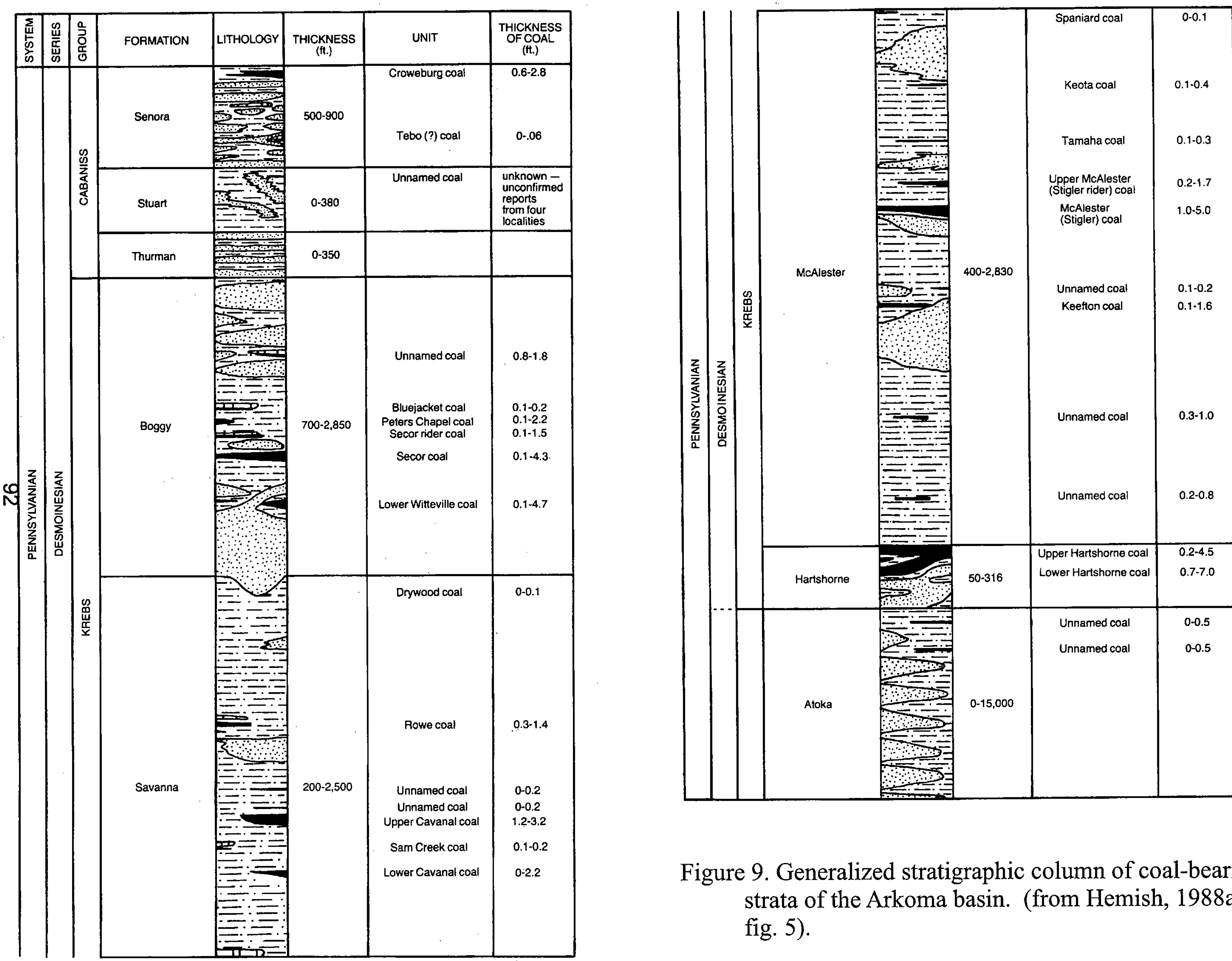

Figure 9. Generalized stratigraphic column of coal-bearing strata of the Arkoma basin. (from Hemish, 1988a, fig. 5).

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Coalbed-methane activity in Oklahoma, 2001

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Coalbed-Methane Activity in Oklahoma, 2001

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ABSTRACT.— Nearly 1,300 wells in the Oklahoma coalfield have been drilled exclusively for coalbed methane (CBM) since 1988, in part for the Section 29 tax credit. A database of CBM completions records 742 completions on the northeast Oklahoma shelf and 552 completions in the Arkoma basin. Operators presently target ten coal objectives on the shelf and five in the basin. The primary CBM objectives, all Desmoinesian (Middle Pennsylvanian) in age, are the Mulky (315 wells) and Rowe (299 wells) coals on the shelf and the Hartshorne coals (519 wells) in the basin.

In general, coals in the Arkoma basin are deeper and thicker than those on the northeast Oklahoma shelf and have higher initial gas rates and lower initial produced-water rates. Many horizontal CBM wells have been drilled in the Arkoma basin since 1998, the more successful wells following improvements in completion techniques. Much is known about the coal geology of the Oklahoma coalfield (e.g., number of coals, age, depth, thickness, rank, quality). The present emphasis is on finding permeable sweet spots and matching coal characteristics to optimum completion techniques.

INTRODUCTION

Commercial production of coalbed methane (CBM) in Oklahoma began in 1988 from the Hartshorne coal at depths ranging from 611 to 716 ft (186 to 218 m). Bear Productions recorded initial-potential (IP) gas rates of 41 to 45 Mcfd (thousand cubic feet of gas per day) per well from seven wells in the Kinta gas field (sec. 27, T.8N., R.20E., Indian Meridian) in Haskell County. Bear Productions was the only CBM operator in Oklahoma from 1988–1990.

The CBM play in Oklahoma began in 1988 with the first completions in the Arkoma basin (**Figure 1**). Following a peak of 71 completions in 1992, activity declined for several years before rising to 97 completions reported in 2000. CBM completions on the shelf began in 1994 with a total of thirteen. Shelf completions totaled 216 in 1998. The apparent decrease in the number of completions from 1998 to 2000 arises from the time lag between when some wells are drilled and when they are reported, and a decrease in drilling activity by companies seeking the balance of Section 29 tax credit in workover wells. When all wells for 1999 and 2000 are reported, the total should be higher. Through July 2001, 1,294 CBM completions have been reported in Oklahoma — 552 in the Arkoma basin and 742 on the northeast Oklahoma shelf.

The coalfield in eastern Oklahoma occupies the southern part of the western region of the Interior Coal Province of the United States (Campbell, 1929; Friedman, 2000). The coalfield is divided into the northeast Oklahoma shelf and the Arkoma basin (Friedman, 1974; **Figure 2**). The commercial coal belt (Fig. 2) contains coal beds of mineable thickness ($\geq$ 10 in. [25 cm] thick and < 100 ft [30 m] deep for surface mining); coal beds in the noncommercial coal-bearing region (Fig. 2) are too thin, of low quality, or too deep for mining. CBM exploration has occurred in both areas.

Figures 3 and 4 are generalized stratigraphic columns of the northeast Oklahoma shelf and Arkoma basin, showing nearly 40 named and several unnamed coal beds and their range in thickness measured from surface exposures and shallow-core samples. Coal beds are 0.1 to 6.2 ft (0.03 to1.9 m) thick on the shelf and 0.1 to 7.0 ft (0.03 to 2.1 m) thick in the basin. The thickest known occurrence of coal in the Oklahoma coalfield is the Hartshorne coal (10 ft) in Latimer County (sec. 35, T.6N., R.18E.; Hemish, 1999) where the Upper and Lower Hartshorne coals coalesced into one bed.

Coal rank, as generalized for all coals at or near the surface, ranges from high-volatile bituminous on the shelf and western Arkoma basin to medium- and low-volatile bituminous in the eastern Arkoma basin in Oklahoma **(Figure 5)**. Rank increases from west to east and with depth in the Arkoma basin, attaining semianthracite in Arkansas. The Hartshorne coal, for example, is medium-volatile bituminous at 2,574 ft (785 m) in the Continental Resources' 1-3 Myers well in Pittsburg County (sec. 3, T.7N., R.16E.) in the high-volatile bituminous area in Figure 5 (see Fig. 14 for location of well).

SOURCE OF DATA

The following discussion of Oklahoma CBM completions is based on information reported to the Oklahoma Corporation Commission and Osage Indian Agency. The names of coal beds are as reported by the operator. For the most part, coal names assigned by operators have not been verified with electric logs, and may not conform to usage accepted by the Oklahoma Geological Survey. Since not all the wells are reported as CBM wells, some interpretation was necessary. Dual completions in sandstone and coal beds, including perforations of more than one coal bed, were made in some wells. Therefore, not all the wells are exclusively CBM completions. Dual completions were included only if gas rates were reported for the coal beds.

This summary is incomplete inasmuch as some wells were not known to be CBM wells or were not reported as such at the time of this compilation. This evaluation is based on reported CBM completions, which may or may not have been connected to a gas pipeline. Likewise, some completions may have produced gas but have since been plugged.

The data summarized in this report have been extracted from the Coalbed-Methane Completions table of the Oklahoma Coal Database. Each record (well completion) in the table lists operator, well name, API number, completion date, location (county, gas field, township-range-section, latitude-longitude), coal bed, production depth interval, initial gas potential and water rates, pressure information, and comments. The database is available for viewing at or purchase from the Oklahoma Geological Survey. A searchable version of the Coalbed-Methane Completions table is accessible on the Internet through a link on the OGS web site, http://www.ou.edu/special/ogs-pttc.

COALBED METHANE ACTIVITY

Northeast Oklahoma Shelf

There have been 742 CBM well completions reported on the shelf by 47 operators through July 2001 (**Figure 6**, excluding one Croweburg coal completion in Okfuskee County). Completions are distributed across Craig, Nowata, Okfuskee, Okmulgee, Osage, Rogers, Tulsa, and Washington Counties. Not all these represent wells drilled specifically for CBM. In fact, about 60% are workovers and recompletions of older conventional gas and oil wells. In ascending order, the coal beds yielding commercial methane include the Riverton (McAlester Formation), Rowe and Drywood (Savanna Formation) and Bluejacket (Boggy Formation) in the Krebs Group; Weir-Pittsburg, Croweburg, Bevier, Iron Post, and Mulky (Senora Formation) in the Cabaniss Group; and Dawson (Holdenville Formation) in the Marmaton Group of Desmoinesian age (Figure 3). Note that the Rowe coal of Kansas and Missouri is equivalent to the Keota coal in Oklahoma, while the Drywood coal of Kansas and Missouri is equivalent to the Spaniard coal in Oklahoma (Hemish, 1990, p. 10).

Figure 7 shows the depth range of CBM completions in 738 wells on the shelf. Coal beds were perforated at depths-to-top of coal of 256 to 2,428 ft (78 to 740 m), for an average depth of 947 ft (289 m). Two modes are apparent. First, the shallower mode represents the Mulky coal (241 wells) completed over a depth range of 256 to 1,732 ft (78 to 528 m); 241 of 321 wells that perforated the Mulky coal were completed in only the Mulky coal. The Mulky, the uppermost coal in the Senora Formation, occurs at the base of the Excello Shale Member (Hemish, 1987) and varies in composition from bituminous coal to carbonaceous shale with increasing amounts of mineral matter. (As determined by Schopf [1956], carbonaceous shale contains >50% mineral matter by weight or <30% carbonaceous matter by volume. According to ASTM [1994], impure coal contains 25 to 50% mineral matter by weight.)

The second mode represents the Rowe coal (299 wells), completed over a depth range of 726 to 2,088 ft (221 to 636 m). The deepest coal completion (2,428 ft) is in the Weir-Pittsburg coal in Osage County (Calumet Oil Co., 7 Catlett well, sec. 32, T.28N., R.8E.). Although two to four coal beds were perforated in 107 completions, only the shallowest coal depth was used in Figure 7.

Initial-potential gas rates from 663 wells range from a trace to 260 Mcfd and average 27 Mcfd (**Figure 8**). However, as will be shown in production-decline curves below, IP rates do not demonstrate the full potential of a CBM well because they reflect only the first of the three stages of a typical CBM production-decline curve: dewatering, followed by stable production and decline (Schraufnagel, 1993). IP gas rates in the Mulky coal range from a trace to 145 Mcfd and in the Rowe coal from 1 to 260 Mcfd. **Figure 9** shows the relationship of depth and initial-potential gas rate for CBM wells on the shelf. The shallowest coals (256-317 ft) had IP rates of 1-8 Mcfd. The shallowest coal with a moderate IP rate of 28 Mcfd was at a depth of 326 ft. Coals with the highest IP rates (>100 Mcfd) were from depths of 561 to 1,463 ft. The maps in **Figures 10 and 11** respectively highlight the Mulky and Rowe CBM wells that exhibit the generally higher rates—29 (12%) of 241 Mulky-only wells with initial gas rates of 50 to 145 Mcfd, and 58 (20%) of 297 Rowe-only wells with initial gas rates of 50 to 260 Mcfd. Four of the eight wells having the highest reported IP rates produce from the Rowe coal in T.25N., R.14E. Those four wells initially produced 130 to 260 Mcfd and 30 to 90 bwpd from depths of 1,136 to 1,190 ft (346 to 363 m).

Production-decline curves for three CBM wells in Nowata and Rogers Counties are illustrated in **Figure 12**. Their IP rates range from 7 to 36 Mcfd and 12 to 120 bwpd. Following a period of 3 to 12 months of erratic production in some wells, gas production can stabilize at more than 1 MMcf (million cubic feet of gas) per month. Maximum monthly production among the three selected wells is 4,664 Mcf (average 155 Mcfd), attained 12 months after completion in the 1 Mitchell well (Figure 12b). Depths-to-top of coal for the three selected wells is 1,113 ft (Figure 12a), 966 ft (Figure 12b), and 1,077 ft (Figure 12c). Gas content and composition data are unavailable for coals on the northeast Oklahoma shelf.

Initial water rates on the shelf range from 0 to 1,201 bwpd and average 60 bwpd from 643 wells (**Figure 13**, excluding one well with 1,201 bwpd). Most of the water is believed to be formation water and not water from fracture stimulation. Because of generally poor water quality, these wells require disposal wells for the produced water. In general, water volumes are not metered; therefore, the volume of disposed water and the effect of water production on gas rate are unknown. Data on water quality is not available.

Arkoma Basin

Figure 14 shows the locations of 552 CBM completions in the basin reported by 44 operators through July 2001. Completions have been reported in Coal, Haskell, Hughes, Latimer, Le Flore, McIntosh, and Pittsburg Counties. In ascending order, the methane-producing coals include the Hartshorne (undivided), Lower Hartshorne, and Upper Hartshorne (Hartshorne Formation), McAlester and "Savanna" (interpreted to be the McAlester coal, McAlester Formation; a completion in Coal County reported to be in the "Lehigh" coal is equivalent to the McAlester coal), Secor (Boggy Formation), and unnamed coal in the Krebs Group of Desmoinesian age (Figure 4). Most (519 completions) of the CBM completions in the Arkoma basin are from Hartshorne coals.

Figure 15 shows the depth range of CBM completions in the basin. Coals in 535 wells were perforated at depths-to-top of coal of 347 to 3,726 ft (106 to 1,136 m), for an average of 1,421 ft (433 m). Three of the four deepest completions, 3,632 to 3,726 ft (1,107 to 1,136 m), were made in the Hartshorne coal in Hughes County (T.4N., R.11E.)(Figure 14). Although 28 completions have perforated two to three coals, only the shallowest coal depth was used in Figure 15.

IP gas rates from 467 wells range from a trace to 1,150 Mcfd (average 106 Mcfd)(**Figure 16**). Most (341 completions) produced 10 to 120 Mcfd. The highest IP rates were reported from the Hartshorne coal. Based on 452 completions with depth and initial potential pairs, **Figure 17** shows no relationship between initial-potential gas rate and depth in the Arkoma basin. Low gas rates (<50 Mcfd) span the entire depth range. The 142 wells (30% of 467) with the highest gas rates (>99 Mcfd) are from depths of 636–3,031 ft (194-924 m), not associated with the deepest completions. Theoretically, gas content increases with increasing rank, depth, and reservoir pressure (Kim, 1977; Scott and others, 1995; Rice, 1996). However, gas production depends on many variables, including gas content, water volume, cleat mineralogy, permeability, porosity, and stimulation method.

The first horizontal or lateral CBM well in Oklahoma was completed by Bear Productions in August 1998. By the end of July 2001, 71 horizontal CBM wells (13% of 552 completions) had been completed in Haskell, Le Flore, and Pittsburg Counties reported by 5 operators—Bear Productions Inc., 5 wells; Brower Oil & Gas Co. Inc., one well; Continental Resources, one well; Mannix Oil Co. Inc., 57 wells; Questar Exploration & Production Co., 7 wells)(**Figure 18**, some areas have two to ten horizontal wells). IP gas rates in the horizontal wells were 15 to 1,150 Mcfd (average of 345 Mcfd) at true vertical depths-to-top of coal of 752 to 3,031 ft (229 to 924 m). Higher gas rates are possible in a horizontal well than in a single-bed vertical well by drilling at a high angle (perpendicular to oblique) to the face cleat to drain a larger area. Vertical CBM wells exhibit an elliptical drainage pattern as a result of the directional (anisotropic) permeability of the cleat (Diamond and others, 1988). Horizontal CBM wells are completed openhole. The lateral distance within the coal for 54 horizontal CBM wells ranged from 439 to 2,523 ft (134 to 769 m), with an average of 1,442 ft (440 m). **Figure 19** is a subset of Figure 17 and shows the relationship of vertical depth-to-top of coal and initial-potential gas rate for 53 horizontal CBM wells in the basin having both depth and IP data.

The map in **Figure 20** shows Hartshorne CBM wells that have the highest initial gas rates—125 (24%) of 519 Hartshorne CBM wells with initial gas rates of 100 to 1,150 Mcfd. A comparison with Figure 18 shows that many of the Hartshorne CBM wells with high gas rates are horizontal CBM wells.

Figure 21 illustrates gas-production-decline curves for five CBM wells in different areas in the Arkoma basin, using monthly production data. IP rates range from 30 to 350 Mcfd and 0 to 75 bwpd. Depths-to-top of coal for the five selected wells is 2,020 ft (Figure 21a), 1,018 ft (Figure 21b), 1,228 ft (Figure 21c), 981 ft (Figure 21d), and 1,351 ft (Figure 21e). The lateral distance within the coal for the horizontal CBM well in Figure 21b is 1,131 ft. Figure 21e extends the data presented in Andrews and others (1998, p. 57, Figure 45a).

Initial produced-water rates from 416 wells range from 0 to 320 bwpd (average 19 bwpd)(**Figure 22**). Most (301 completions) produced less than 20 bwpd. Most Arkoma basin CBM well completions are situated on the flanks of anticlines (**Figure 23**) and tend to produce relatively little water. An undisclosed amount of initial water production is frac water introduced during fracture stimulation.

Andrews and others (1998) summarized published information on gas resources, gas content, gas composition, and cleating in Hartshorne coals. Measured gas contents in the Arkoma basin range from 70 to 560 cf/ton in high-volatile to low-volatile bituminous coal cores from depths of 175 to 3,651 ft (53 to 1,113 m).

CONCLUSIONS

The Oklahoma CBM play began in the Arkoma basin in 1988. The play then spread to the northeast Oklahoma shelf in 1994. Through July 2001, 1,294 CBM completions were reported in Oklahoma — 552 in the Arkoma basin and 742 on the northeast Oklahoma shelf. The primary objectives are Hartshorne coals in the basin and the Mulky and Rowe coals on the shelf. Fourteen percent (107 of 742) of the CBM completions on the shelf were multiple-coal completions with two to four coal beds, while most of the CBM completions in the basin were single-coal completions.

Coal completion depths range from 256 to 2,428 ft (78 to 740 m) and average 947 ft (289 m) in 738 wells on the shelf, and 347 to 3,726 ft (106 to 1,136 m), averaging 1,421 ft (433 m) in 535 wells in the basin.

Initial-potential gas rates range from a trace to 260 Mcfd (average 27 Mcfd) from 663 wells on the shelf, and a trace to 1,150 Mcfd (average 106 Mcfd) from 467 wells in the basin. The maximum initial gas rate was reported in the Hartshorne coal at a true vertical depth of 1,604 ft (489 m) from a horizontal well in Haskell County.

Produced-water rates range from 0 to 1,201 bwpd (average 60 bwpd) from 643 wells on the shelf, and 0 to 320 bwpd (average 19 bwpd) from 416 wells in the basin.

Low initial gas rates and minimal initial increase in gas production during dewatering are often attributed to formation damage caused by well stimulation, including the generation of coal fines that plug permeability. Present industry emphasis is on matching the completion techniques to the specific coal.

Future development of CBM in Oklahoma is promising. Applications of horizontal drilling and established completion practices have demonstrated the potential for CBM in the Midcontinent USA.

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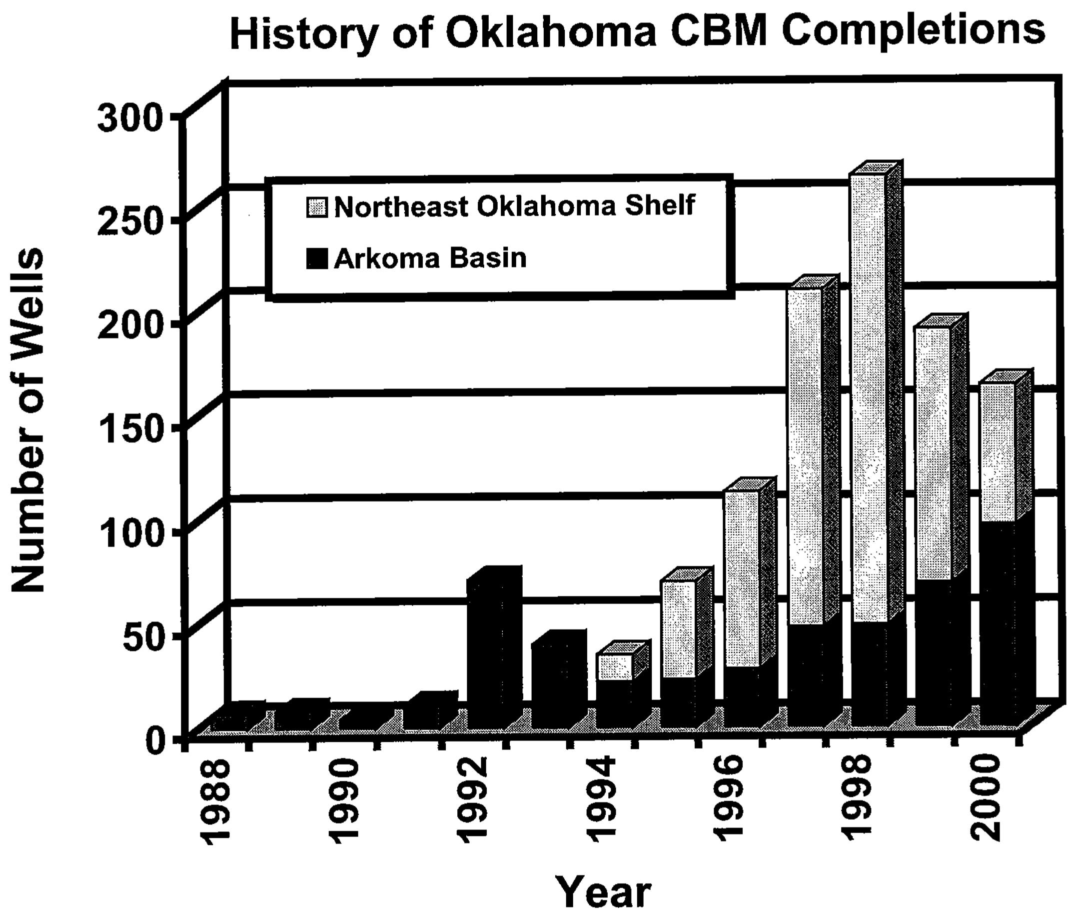


Figure 1. Histogram showing numbers of Oklahoma coalbed-methane well completions, 1988 to 2000.

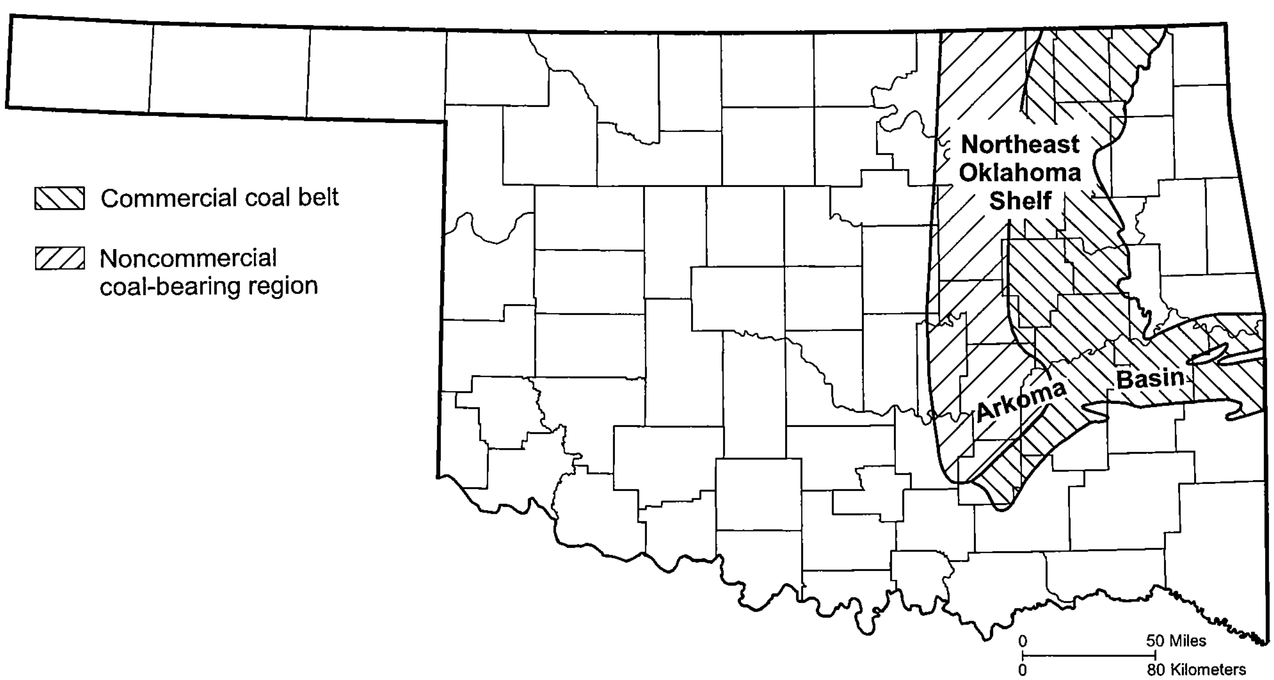


Figure 2. Map of Oklahoma coalfield. Modified from Friedman (1974).

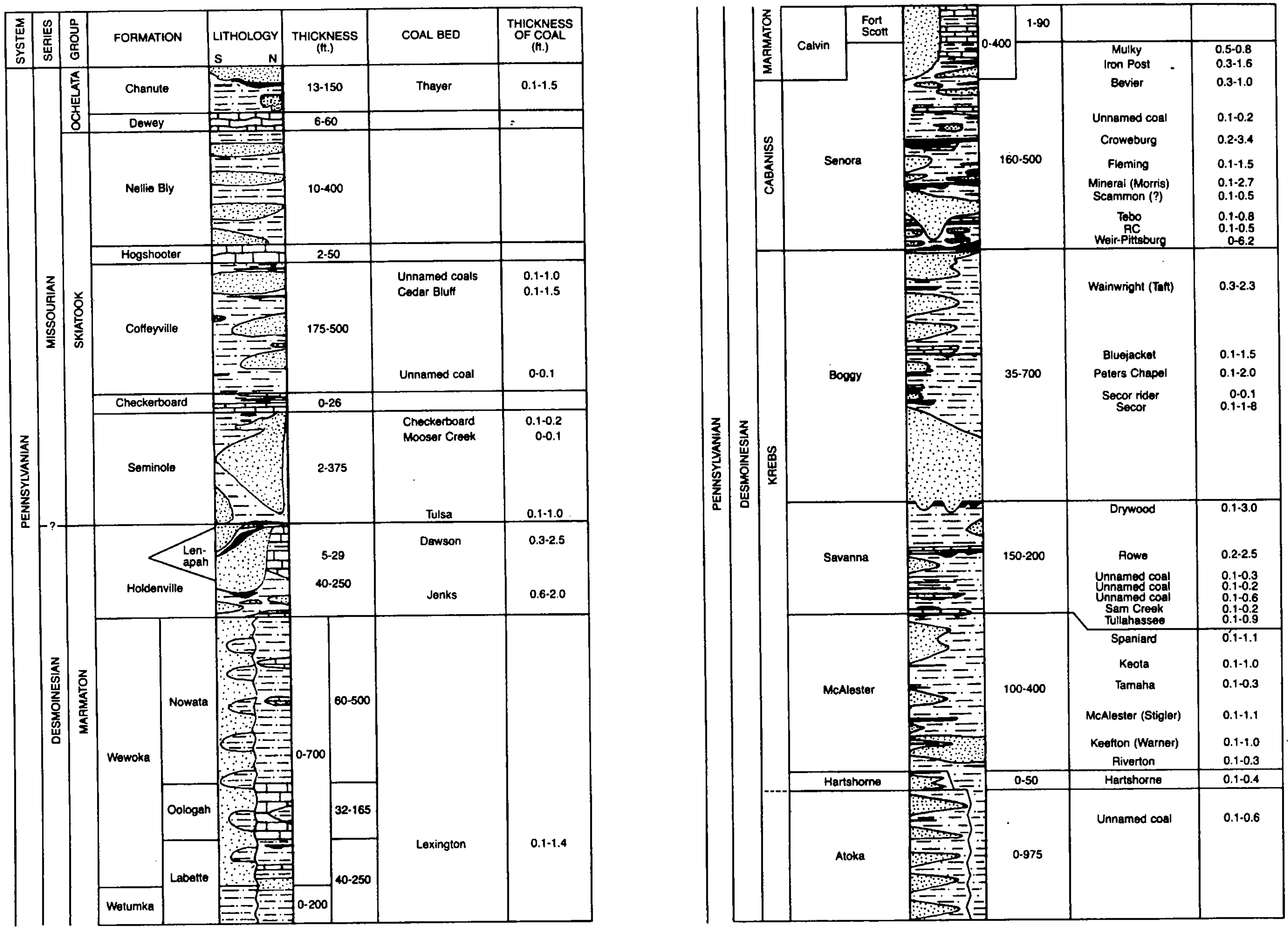


Figure 3. Generalized stratigraphy of coal-bearing strata of the northeast Oklahoma shelf. From Hemish (1988).

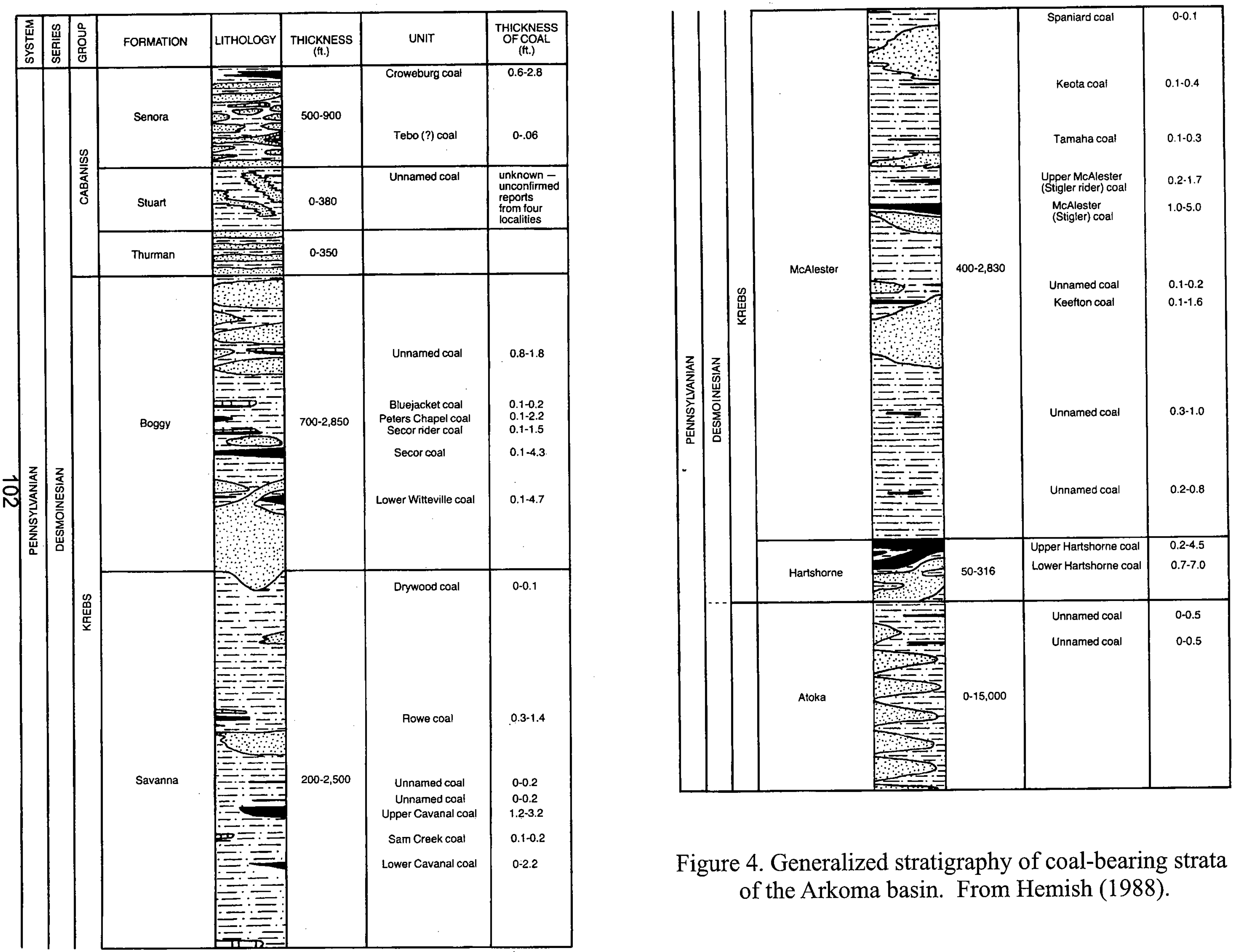


Figure 4. Generalized stratigraphy of coal-bearing strata of the Arkoma basin. From Hemish (1988).

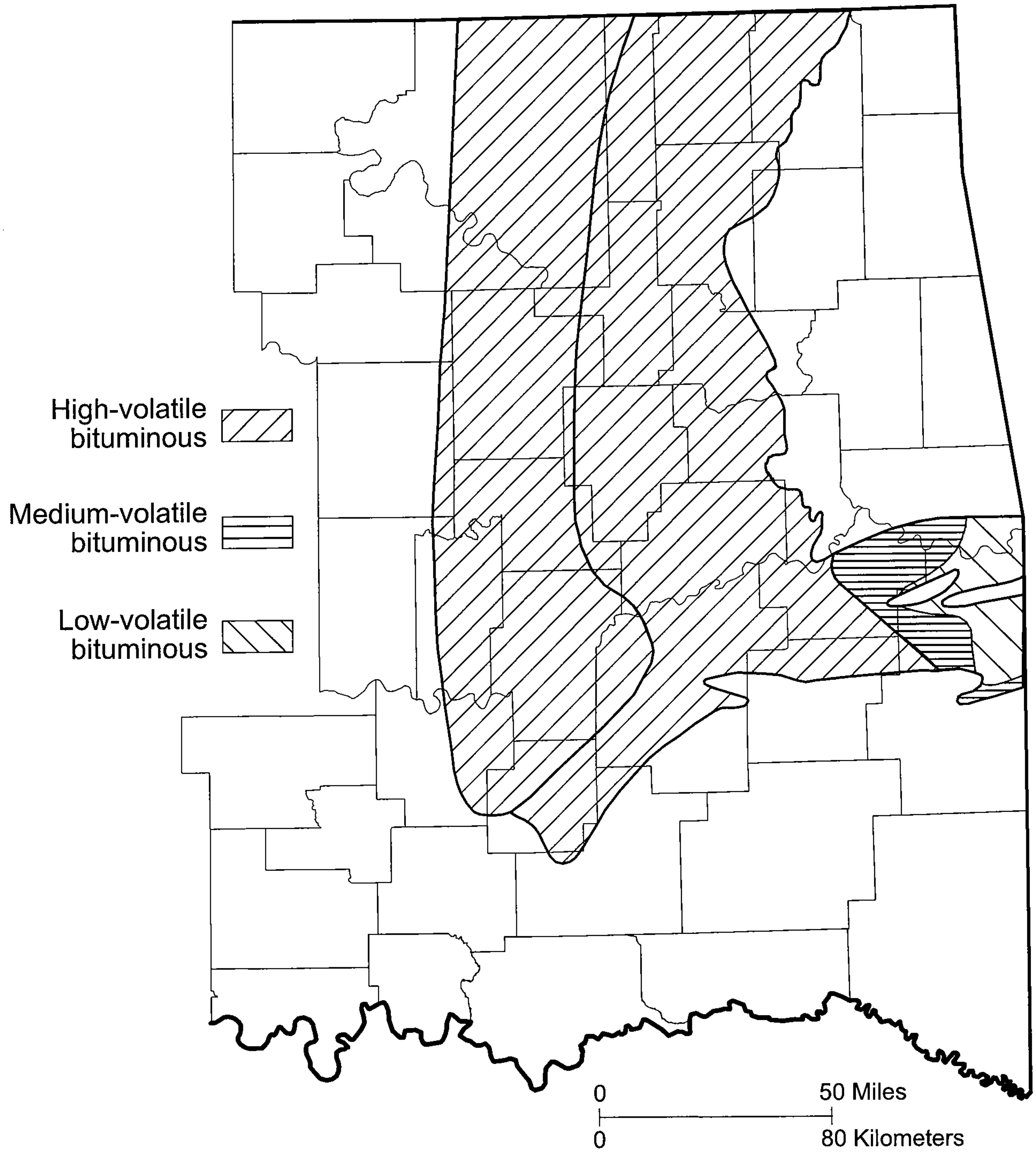


Figure 5. Generalized rank of coal beds near the surface in the Oklahoma coalfield. Modified from Friedman (1974) and Andrews and others (1998).

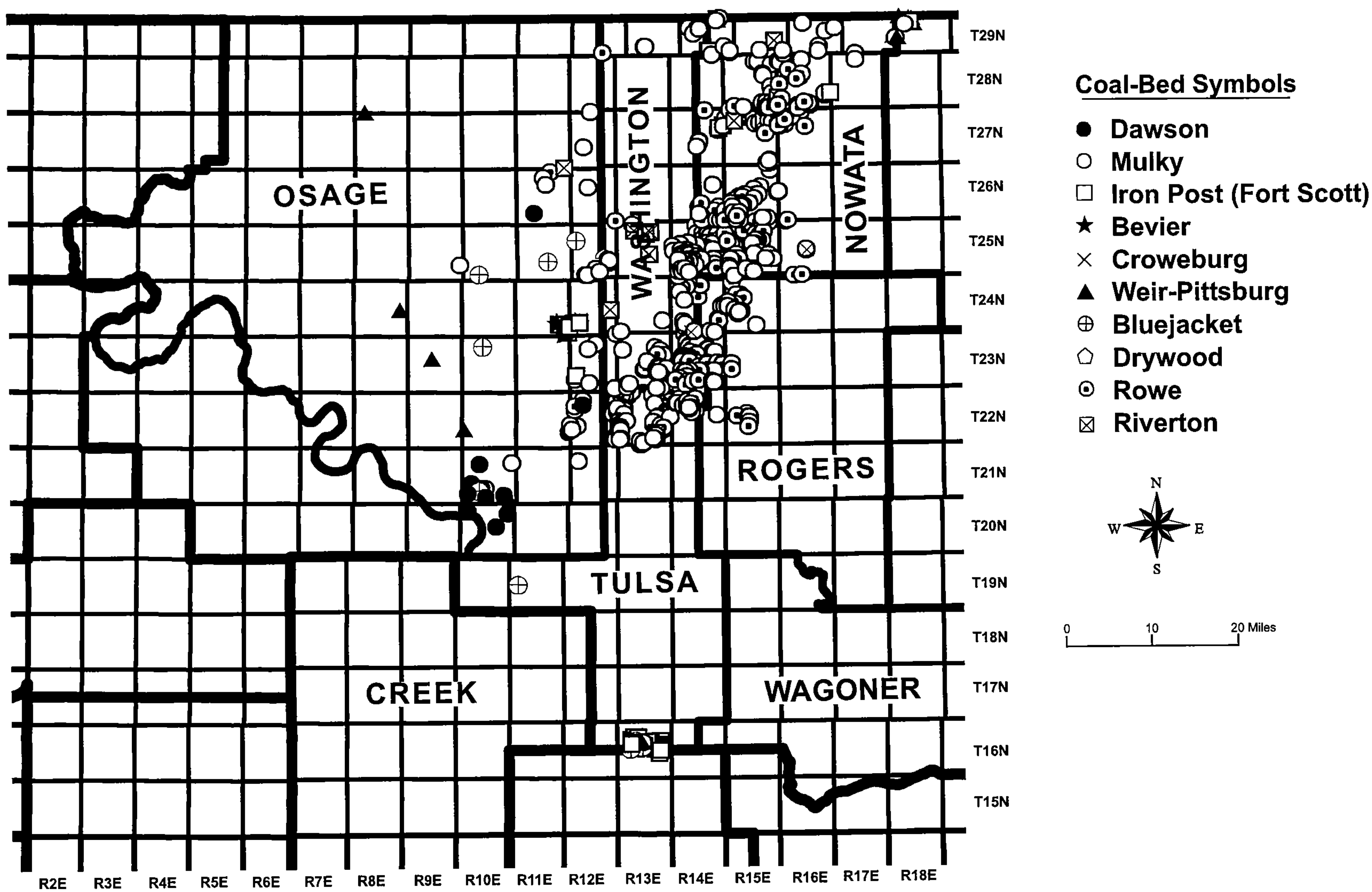


Figure 6. Distribution of coalbed-methane well completions by coal bed on the northeast Oklahoma shelf.

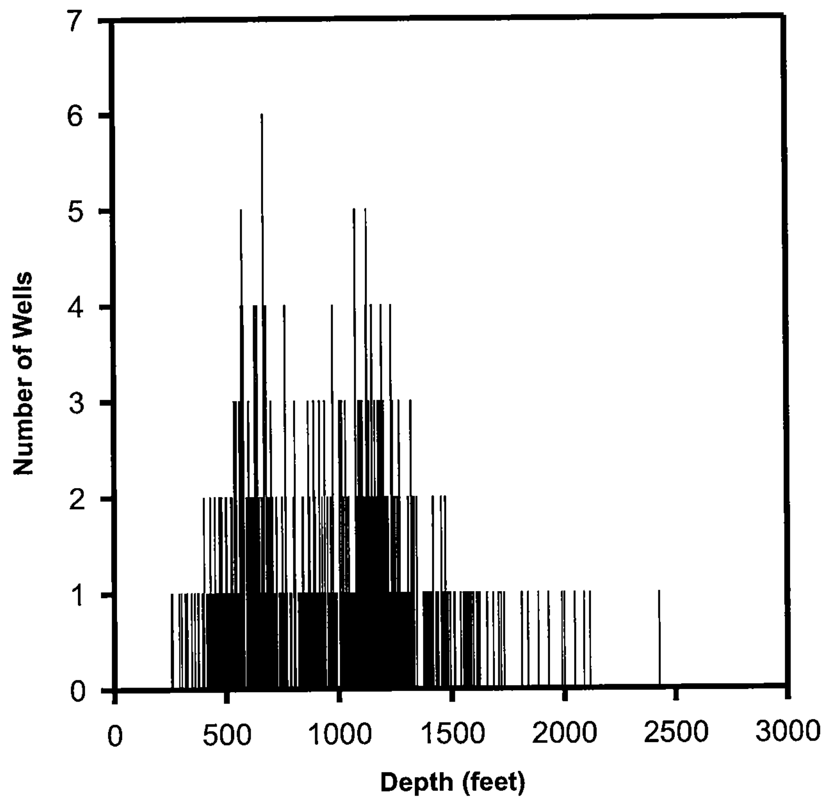


Figure 7. Histogram of coalbed-methane well completion depths on the northeast Oklahoma shelf.

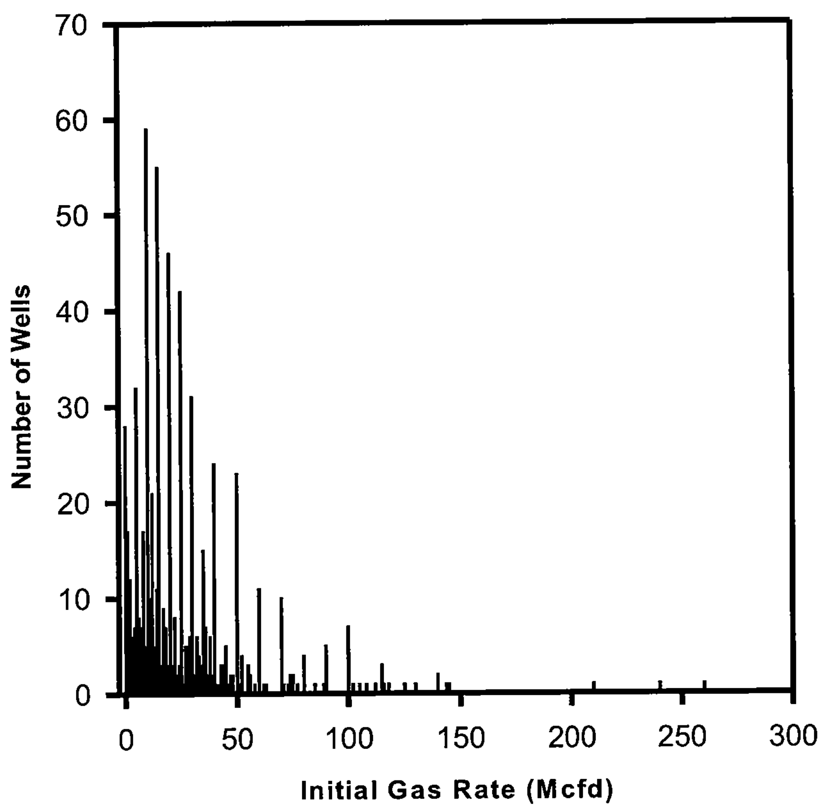


Figure 8. Histogram of initial-potential-gas rates in coalbed-methane well completions on the northeast Oklahoma shelf.

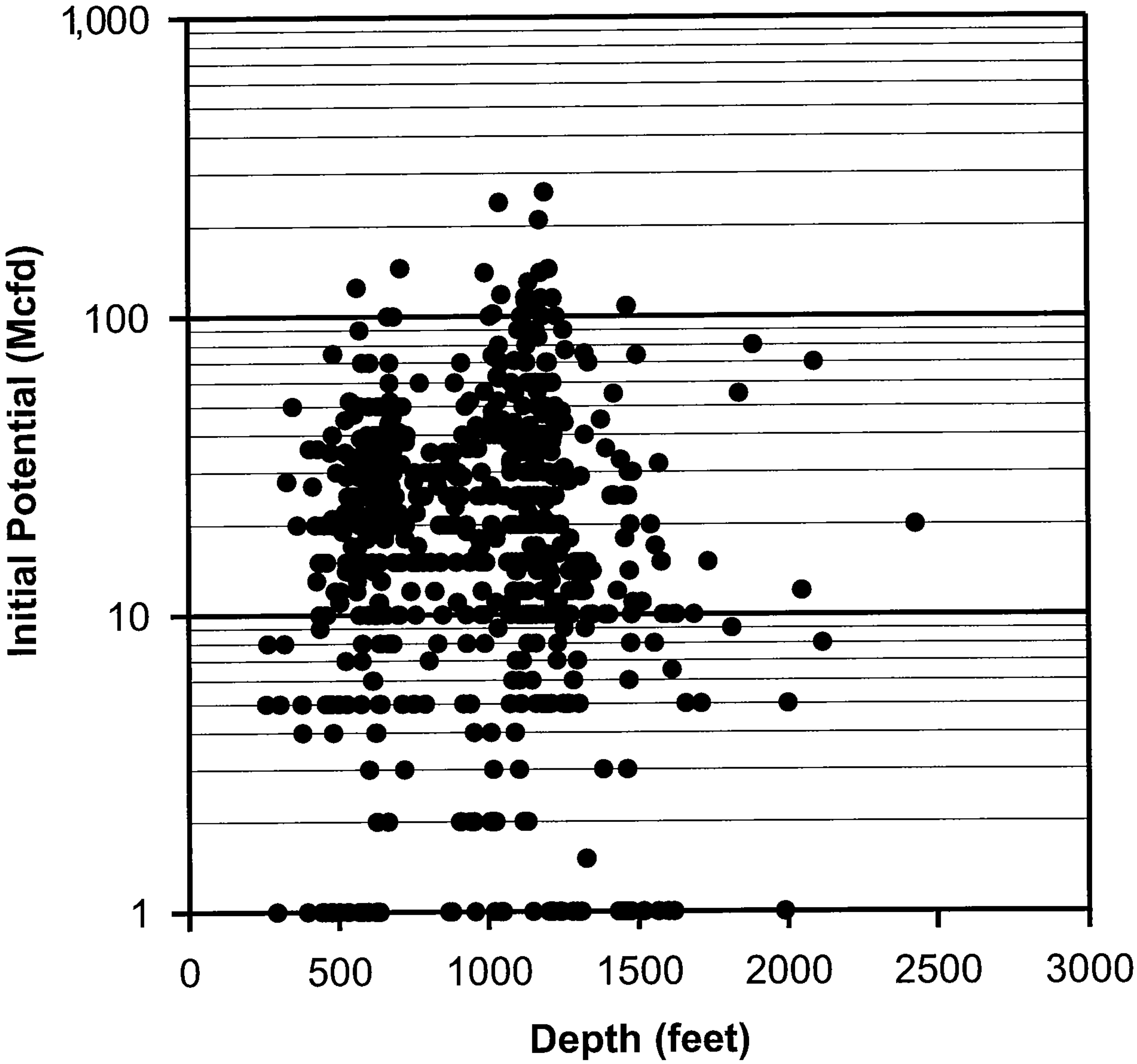


Figure 9. Scatter plot of initial-potential-gas rate (in thousand cubic feet of gas per day–Mcfd) and depth (in feet) to top of coal on the northeast Oklahoma shelf.

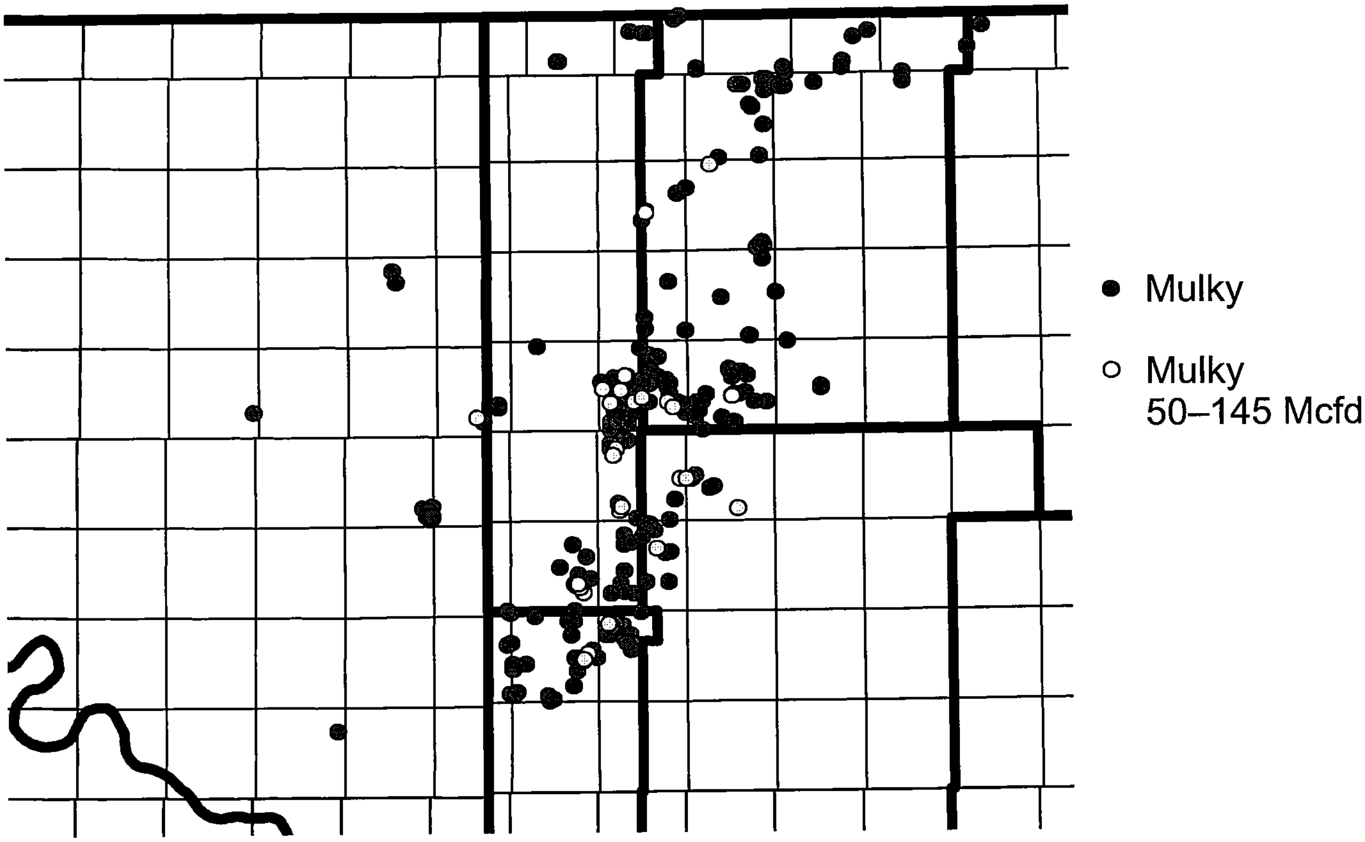


Figure 10. Distribution of well completions in the Mulky coal on the northeast Oklahoma shelf, showing wells with relatively high IP gas rates.

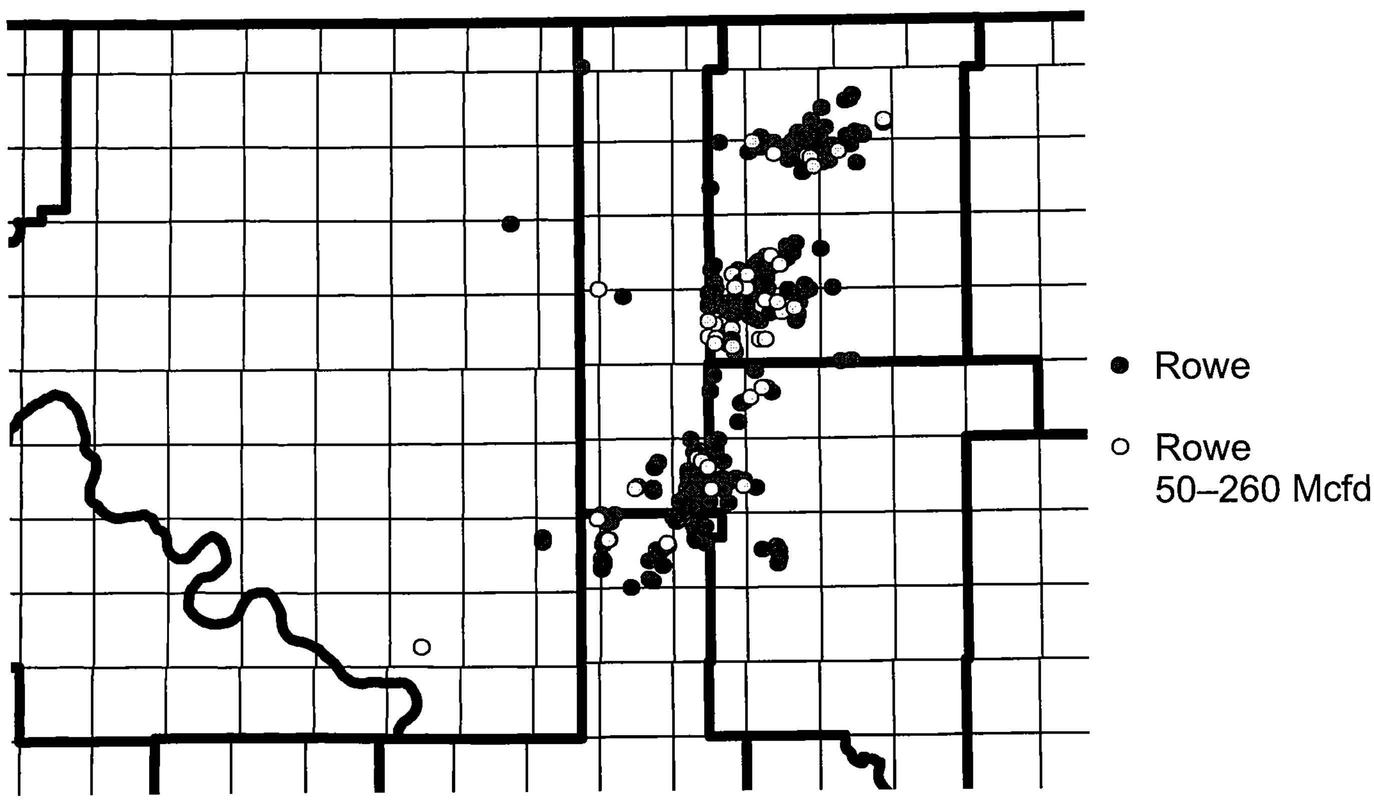
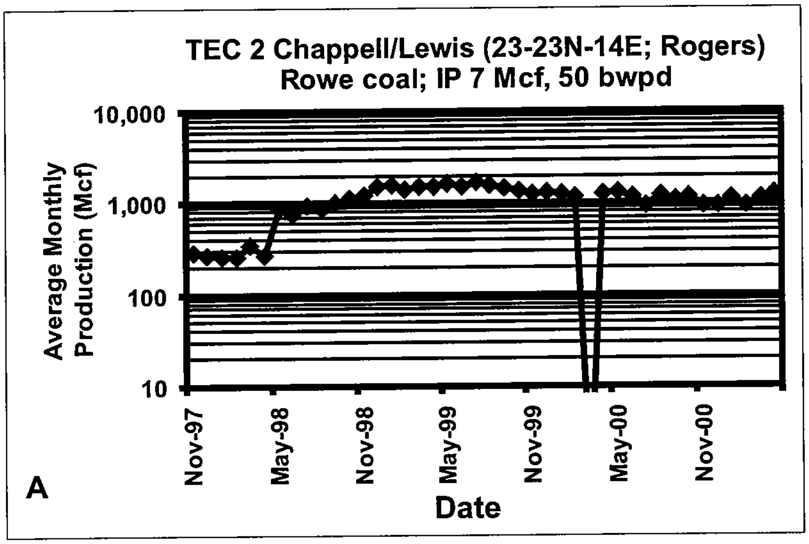
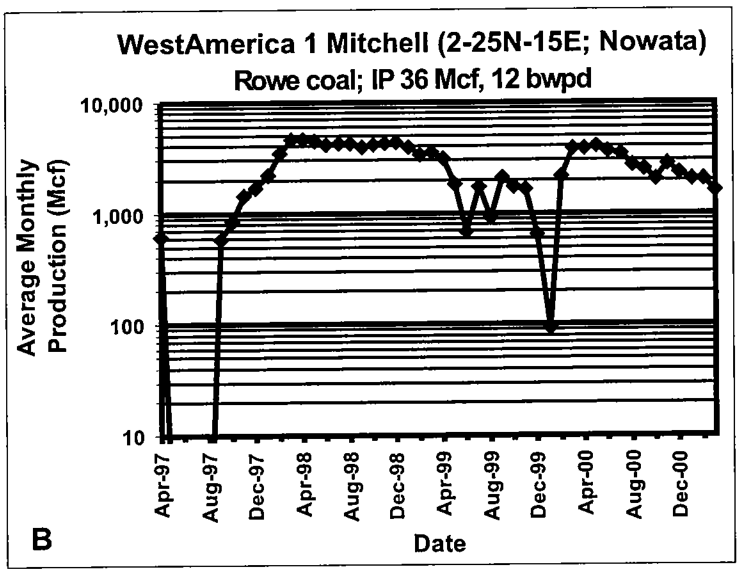


Figure 11. Distribution of well completions in the Rowe coal on the northeast Oklahoma shelf, showing wells with relatively high IP gas rates.





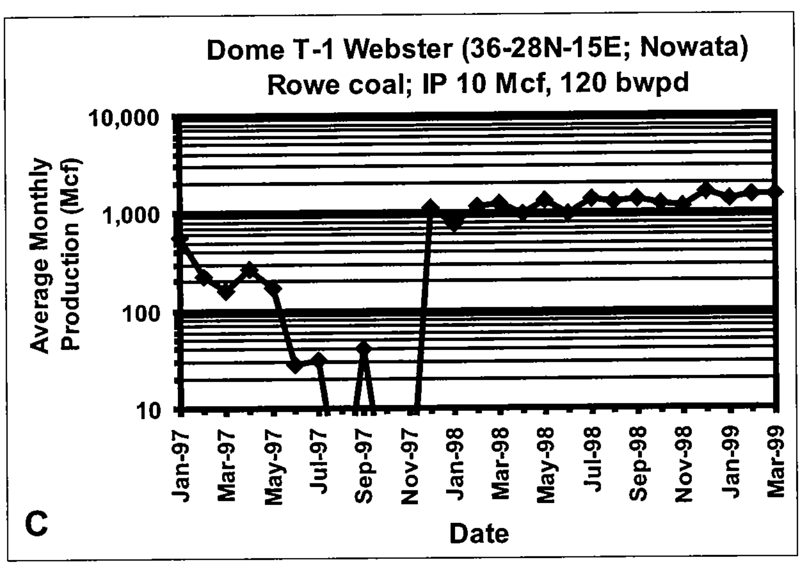


Figure 12. Gas-production-decline curves. (A) TEC Resources 2 Chappell/Lewis well. (B) WestAmerica Corporation 1 Mitchell well. (C) Dome Engineering T-1 Webster well.

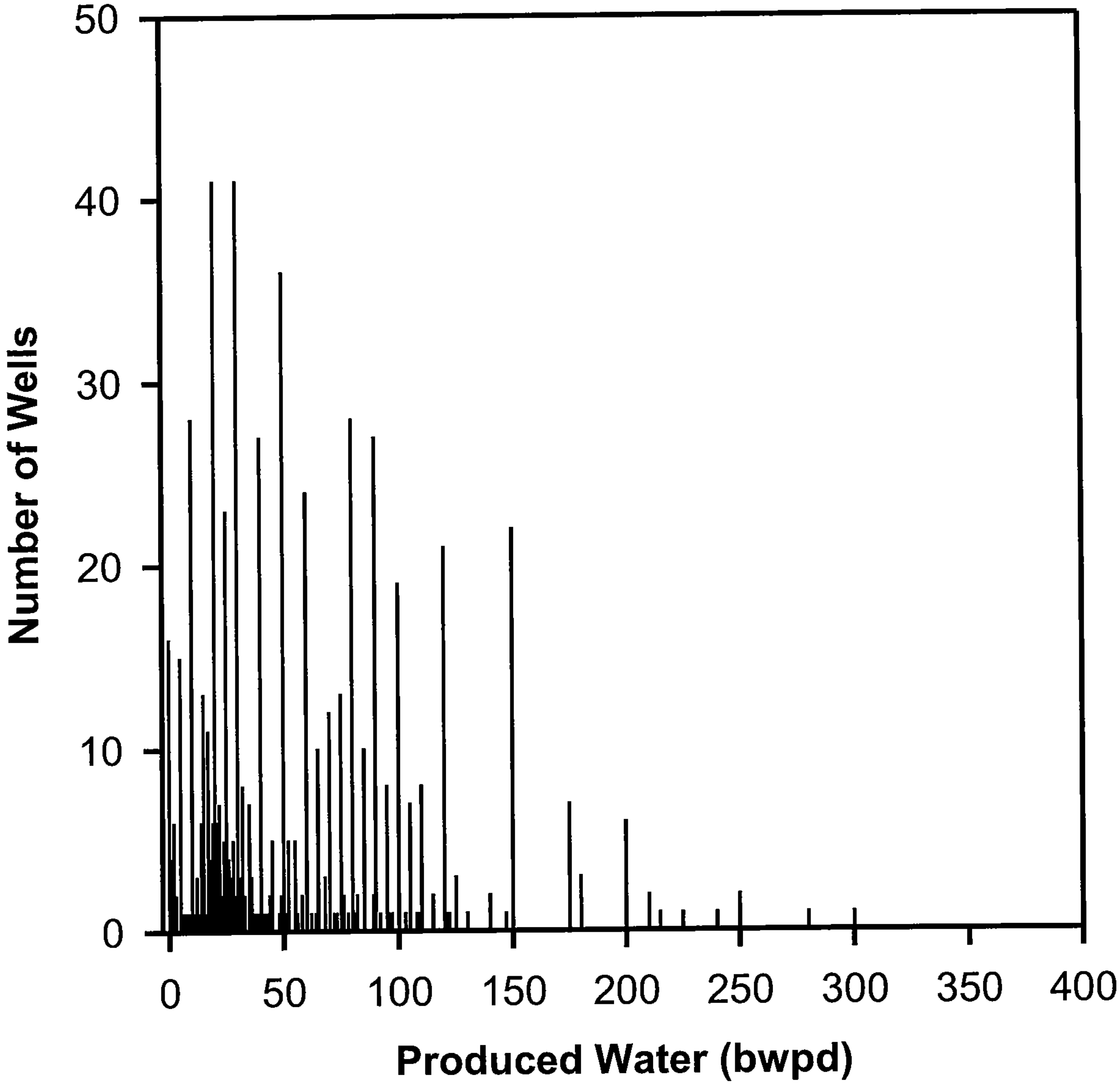


Figure 13. Histogram of initial water production rates from coalbed-methane wells on the northeast Oklahoma shelf (excluding one well with 1,201 bwpd).

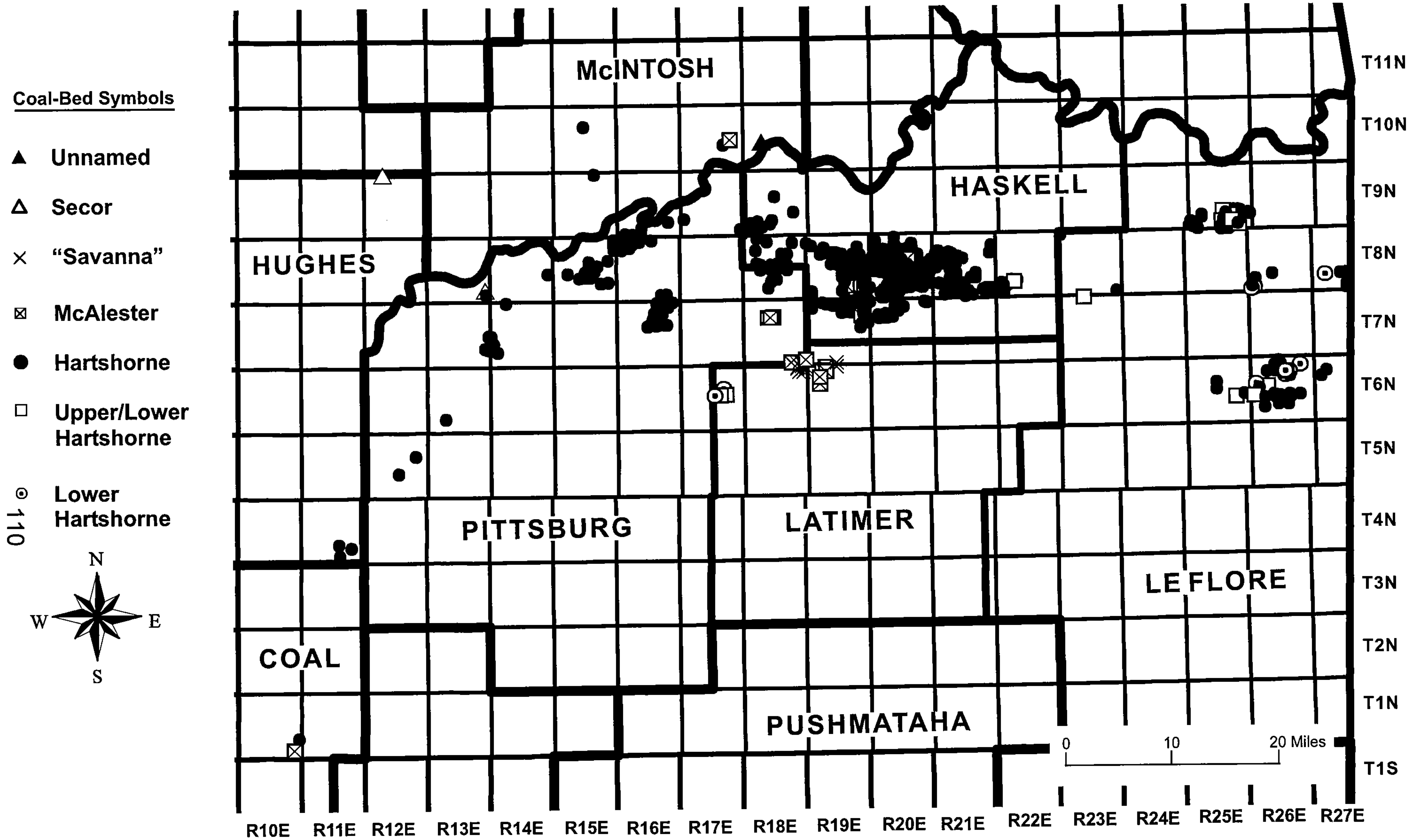


Figure 14. Distribution of coalbed-methane well completions by coal bed in the Arkoma basin.

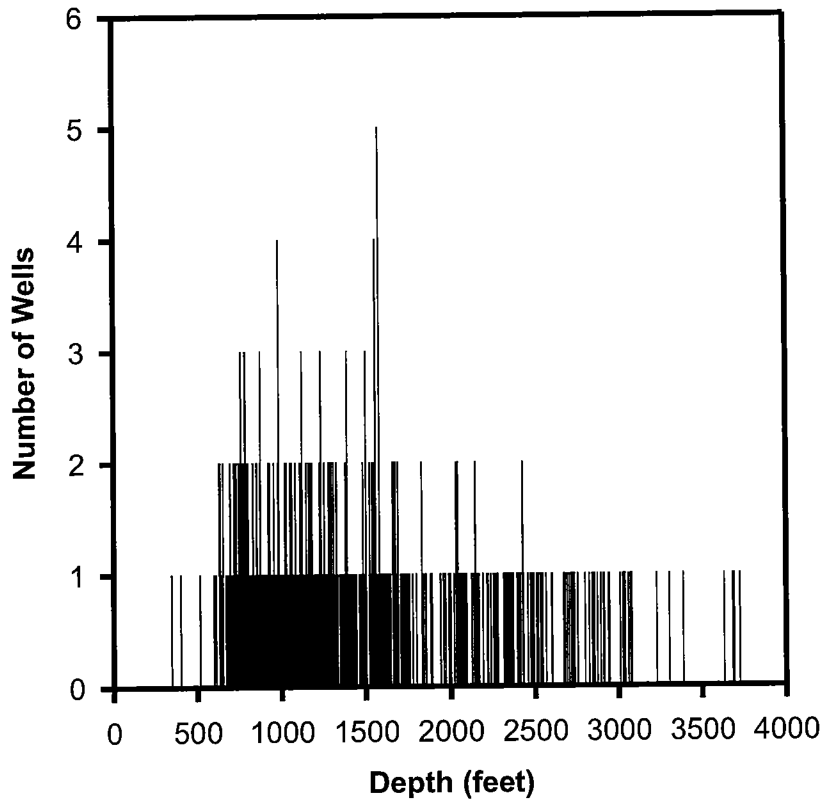


Figure 15. Histogram of coalbed-methane well completion depths in the Arkoma basin.

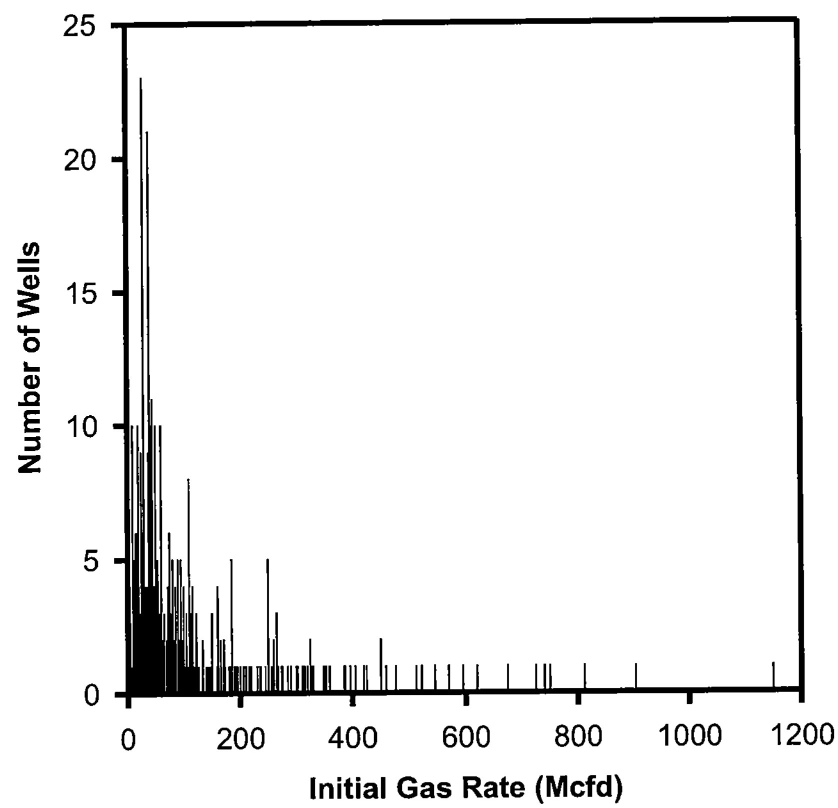


Figure 16. Histogram of initial-potential-gas rates in coalbed-methane well completions in the Arkoma basin.

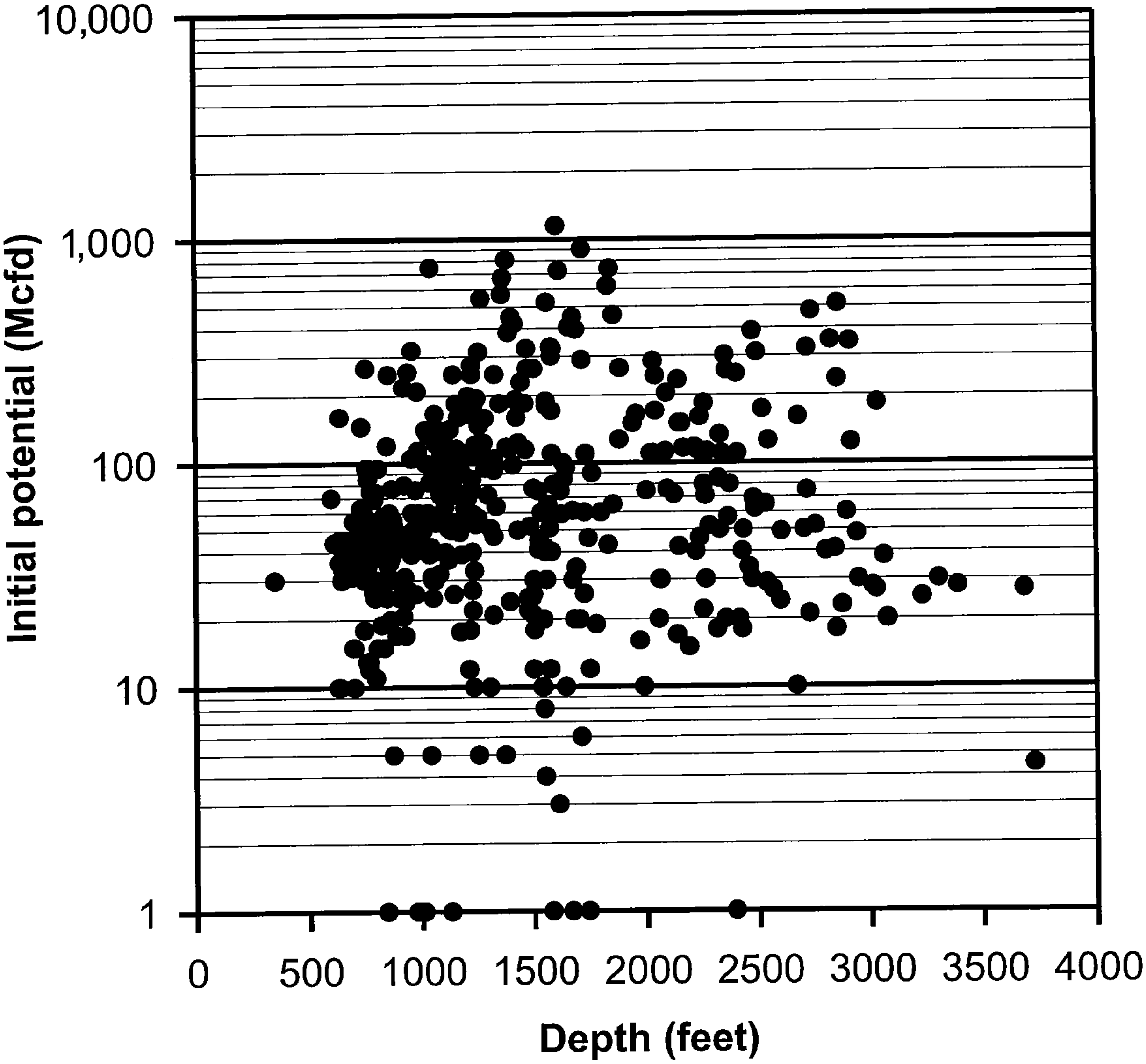


Figure 17. Scatter plot of initial-potential-gas rate (in thousand cubic feet of gas per day–Mcfd) and depth (in feet) to top of coal in the Arkoma basin.

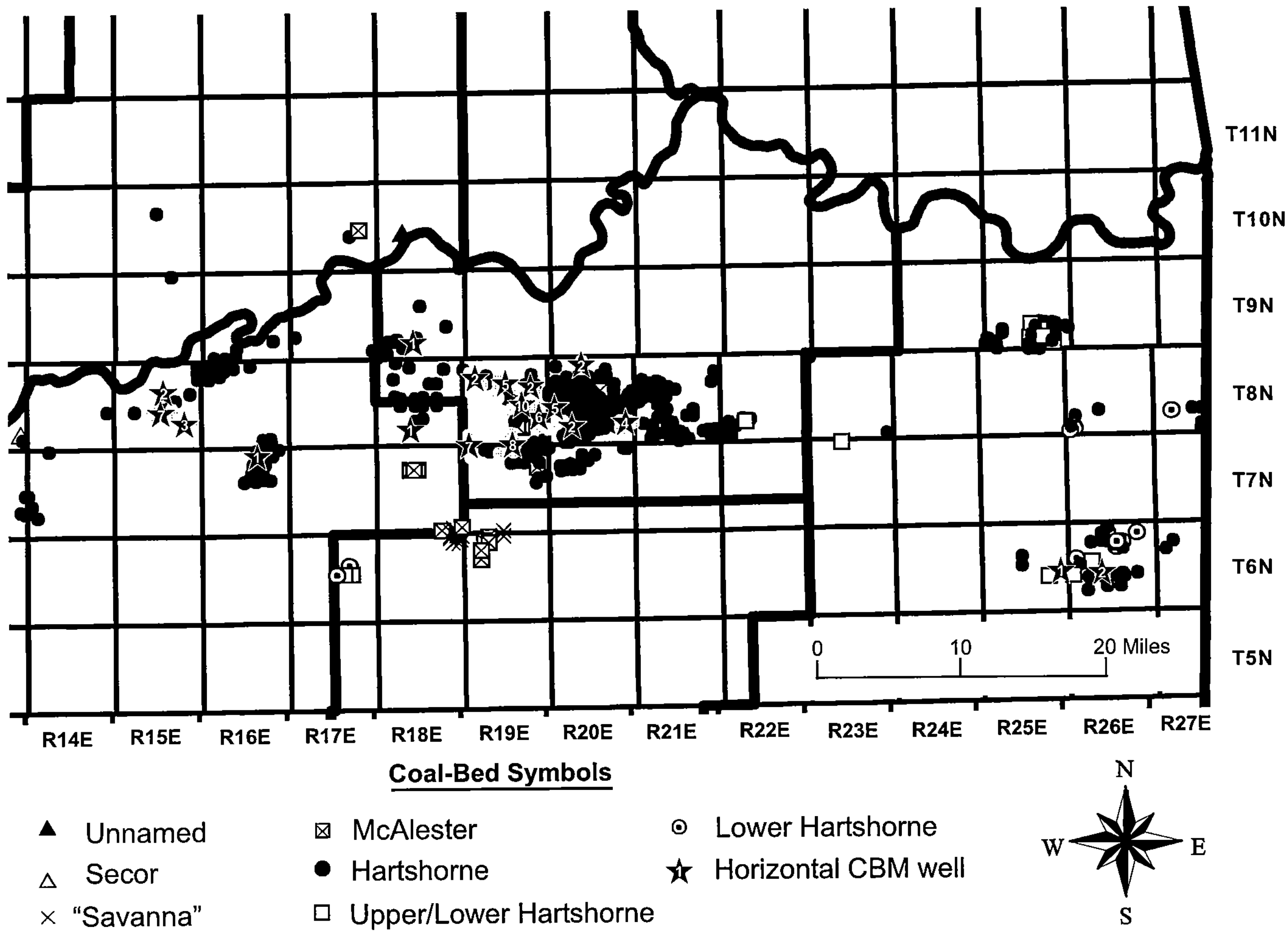


Figure 18. Distribution of horizontal coalbed-methane well completions in the Arkoma basin.

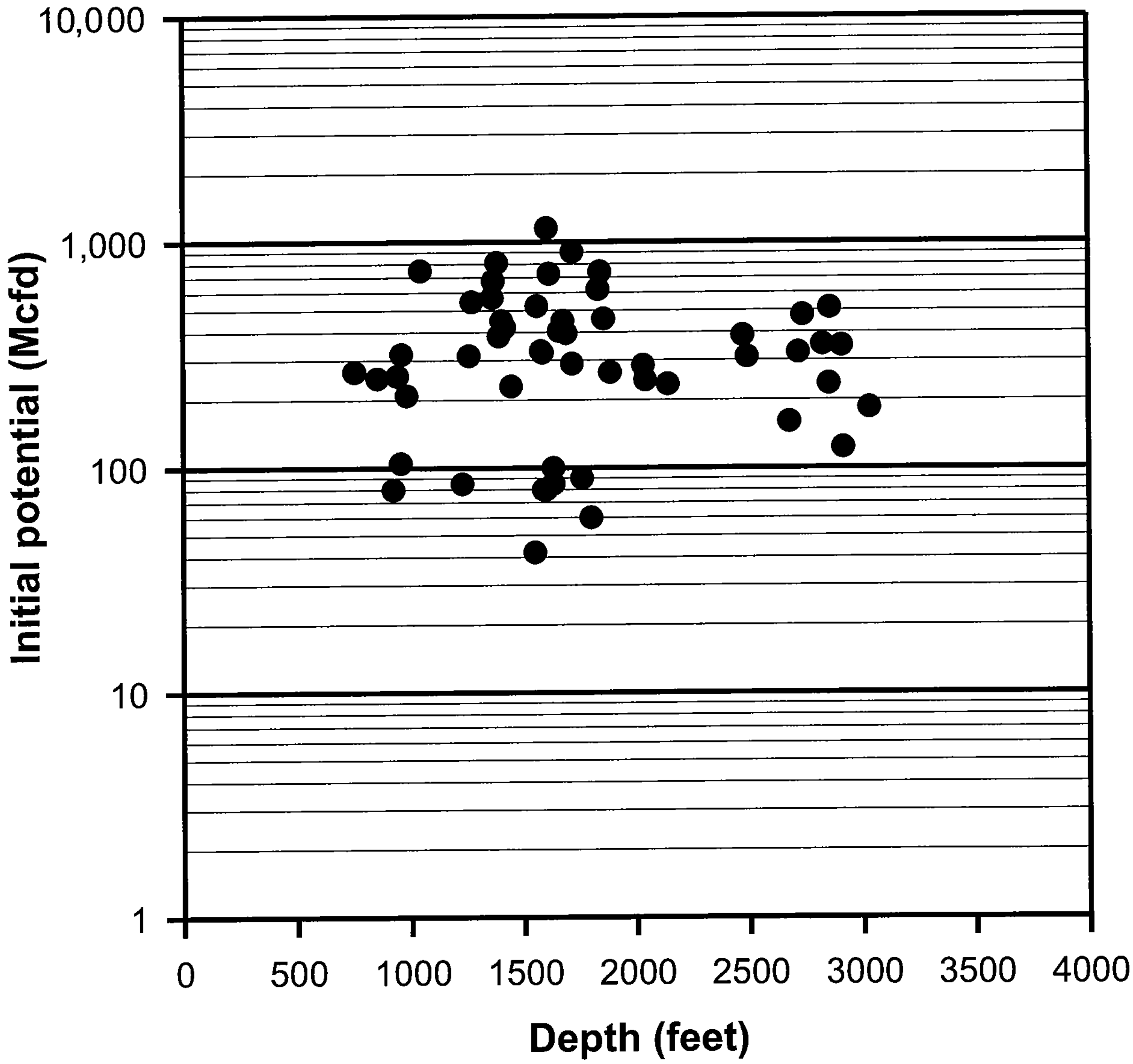


Figure 19. Scatter plot of initial-potential-gas rate (in thousand cubic feet of gas per day–Mcfd) and depth (in feet) to top of coal in the Arkoma basin horizontal CBM wells.

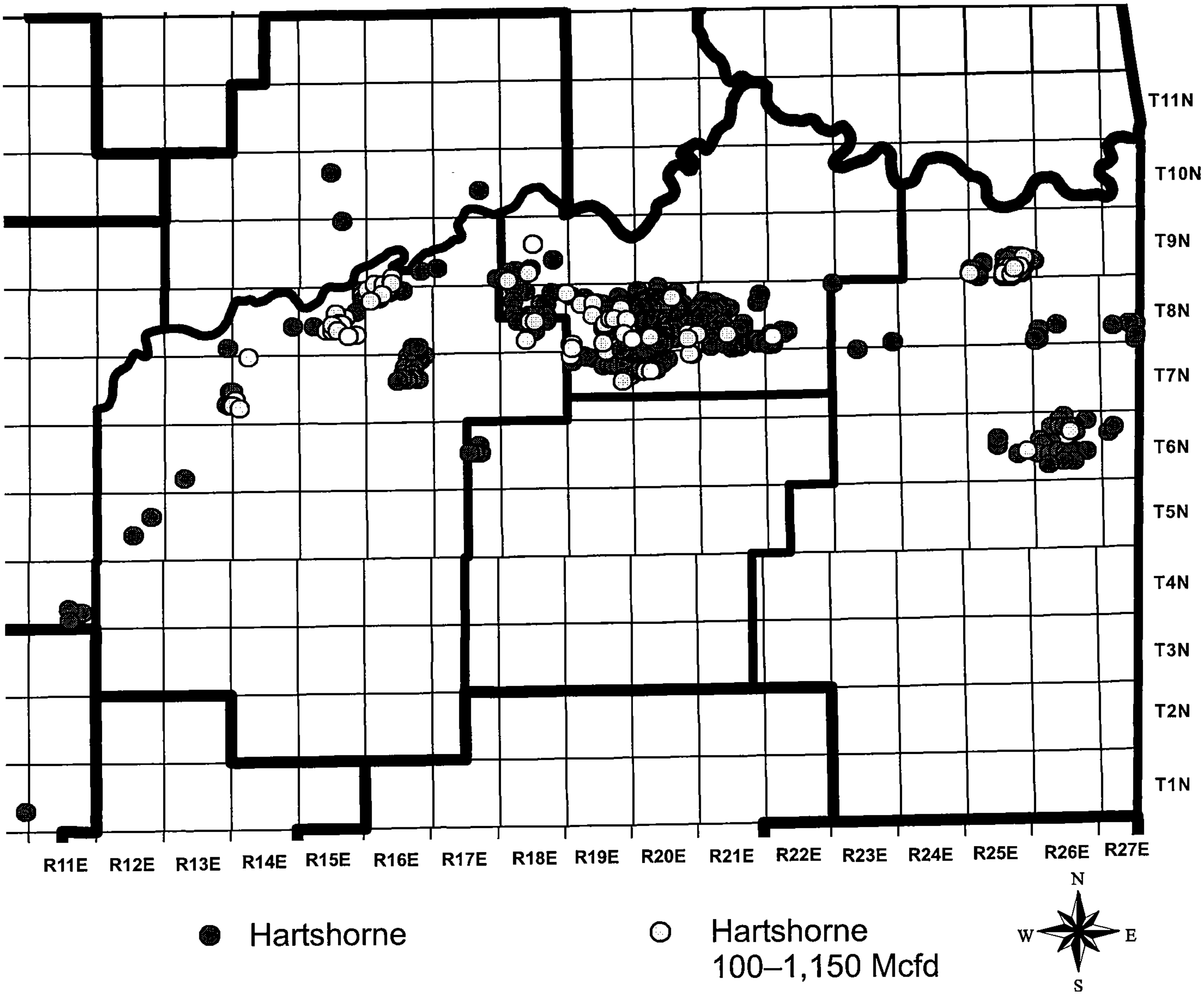
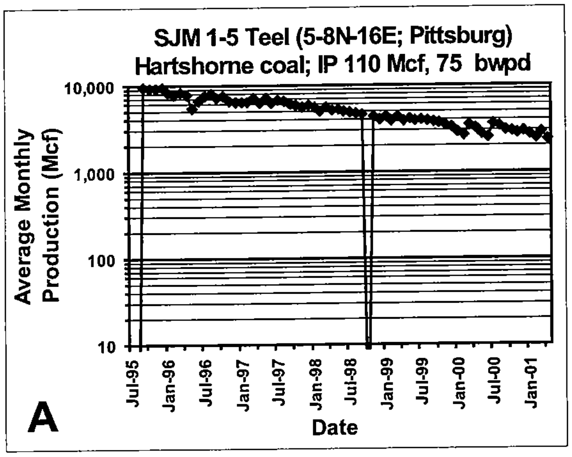
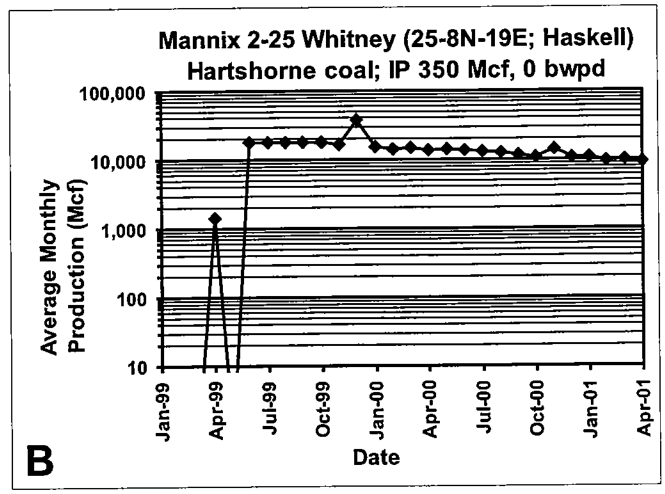
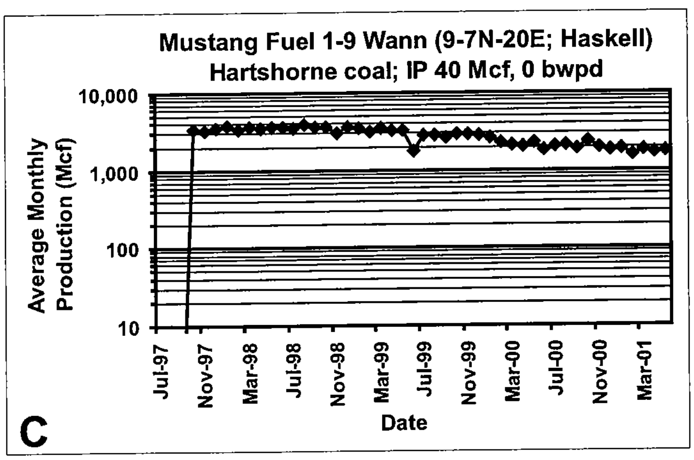
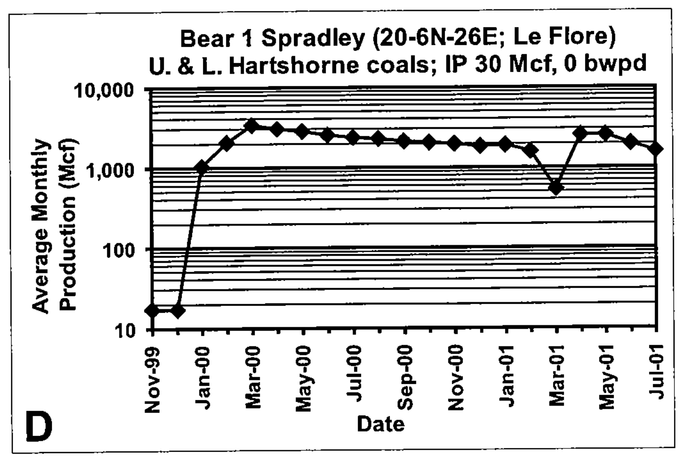


Figure 20. Distribution of well completions in the Hartshorne coal in the Arkoma basin, showing wells with relatively high IP gas rates.









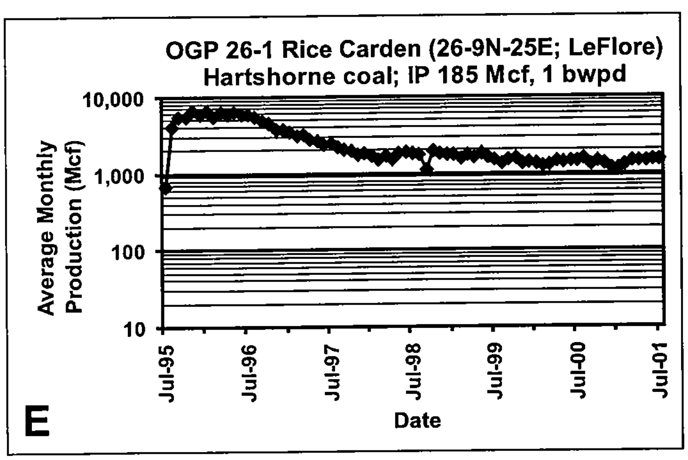


Figure 21. Gas-production-decline curves. (A) SJM Inc. 1-5 Teel well. (B) Mannix Oil 2-25 Whitney well. (C) Mustang Fuel 1-9 Wann well. (D) Bear Productions 1 Spradley well. (E) OGP Operating 26-1 Rice Carden well.

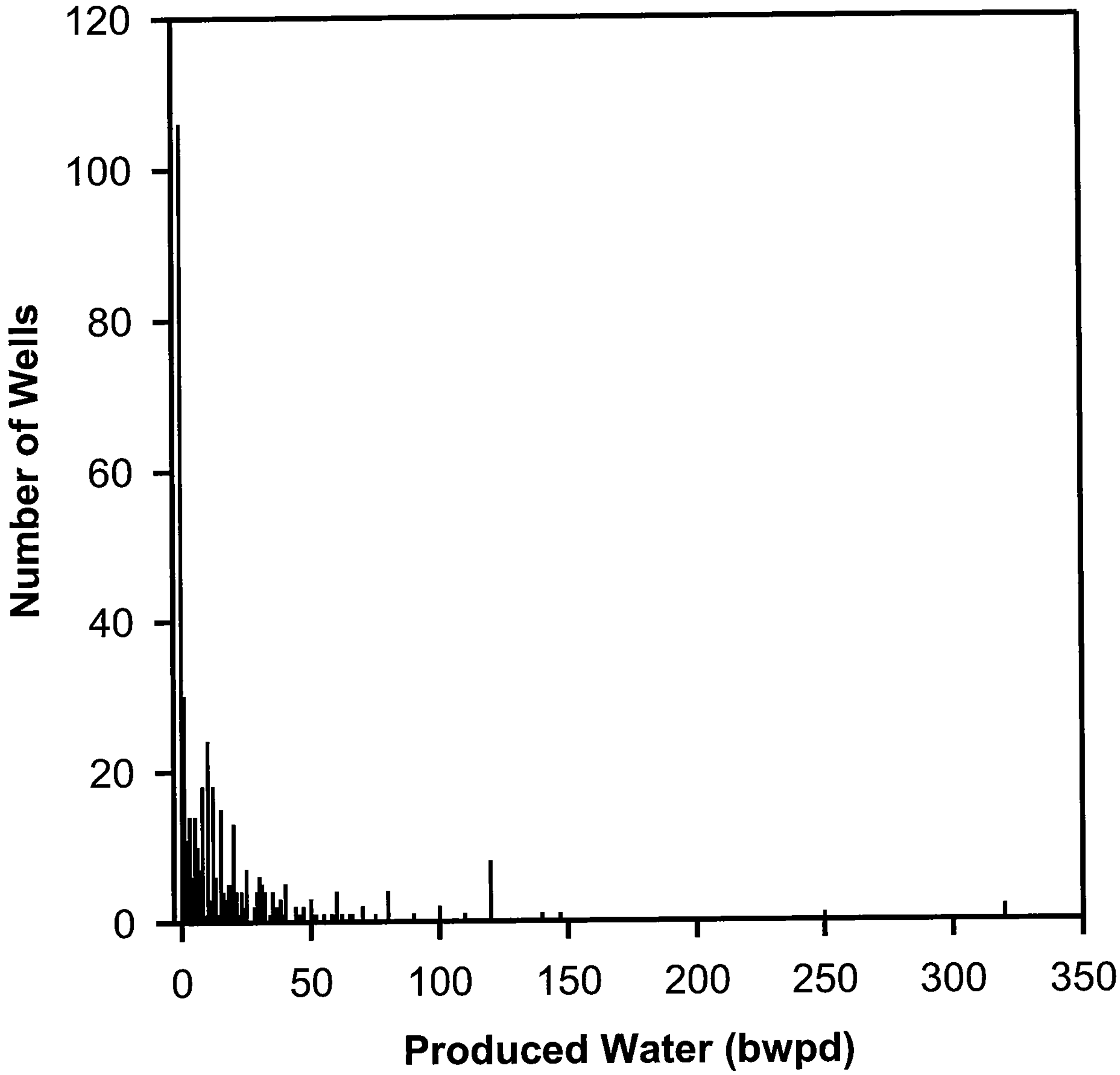
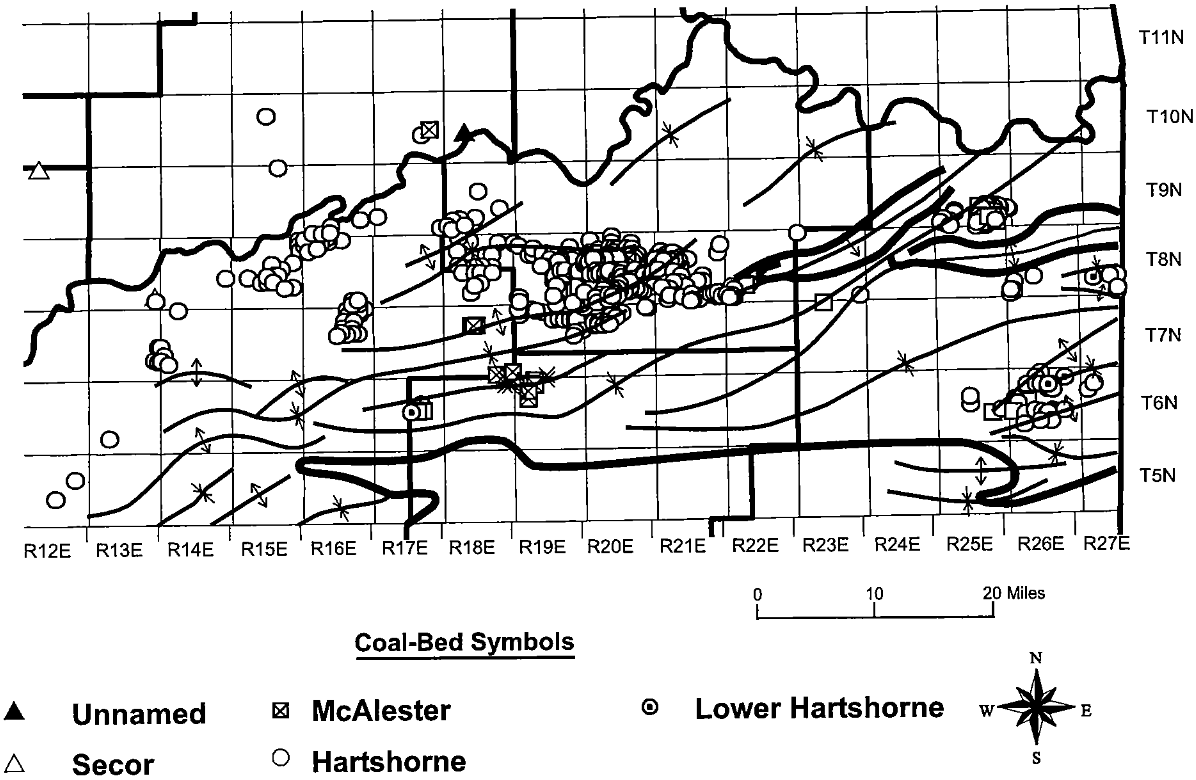


Figure 22. Histogram of initial water production rates from coalbed-methane wells in the Arkoma basin.



Coal-Bed Symbols

▲ Unnamed
△ Secor
× "Savanna"
⊠ McAlester
○ Hartshorne
□ Upper/Lower Hartshorne
⊙ Lower Hartshorne

Figure 23. Major surface folds, Hartshorne coal outcrop, and coalbed-methane well completions in the Arkoma basin, Oklahoma. Structure modified from Arbenz (1956, 1989), Berry and Trumbly (1968), and Suneson (1998).

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

6

Arkoma basin coalbed-methane potential and practices

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Wendell, J.H., Jr., 2001, Arkoma basin coalbed-methane potential and practices, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 119-139.

ARKOMA BASIN COALBED POTENTIAL & PRACTICES

10 OCTOBER 2001
OGS Conference
Poteau, Oklahoma

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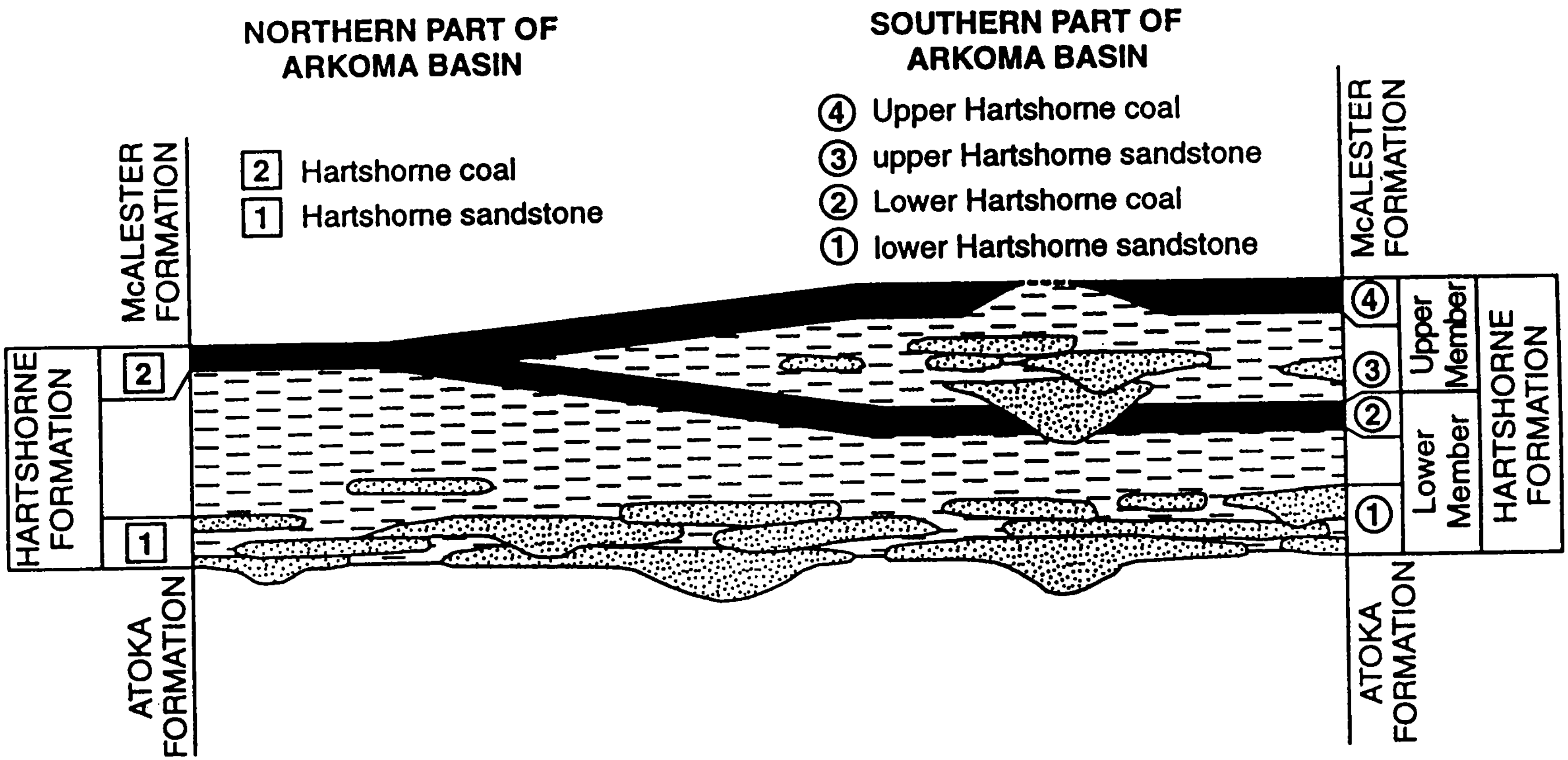
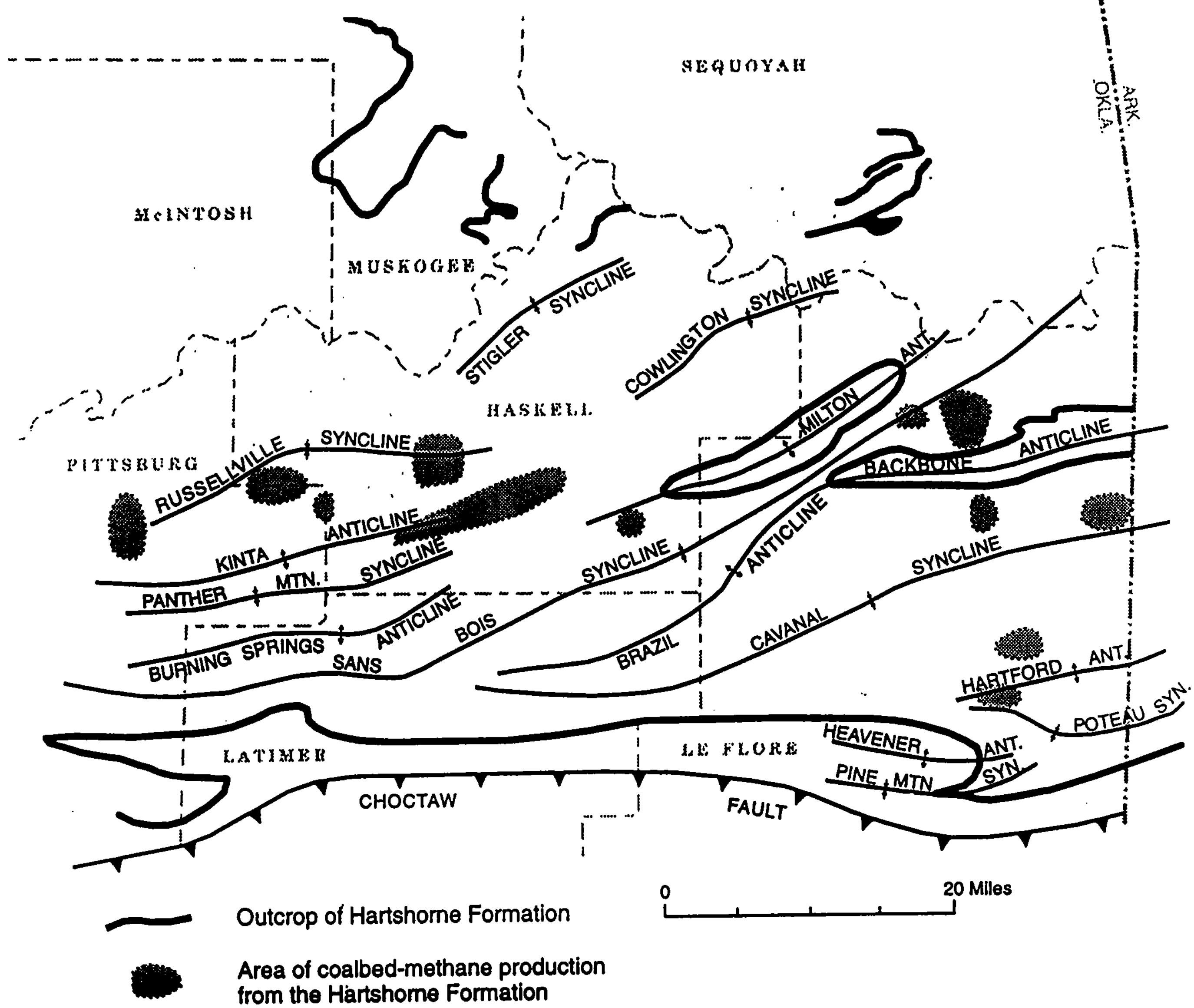
ARKOMA BASIN CBM POTENTIAL

- FACTORS CRITICAL TO CBM PRODUCIBILITY
  - DEPOSITION & DISTRIBUTION OF COAL
  - STRUCTURE & STRESSES
  - COAL RANK & TREND
  - PERMEABILITY
  - HYDRODYNAMIC PROFILES
  - GAS CONTENT

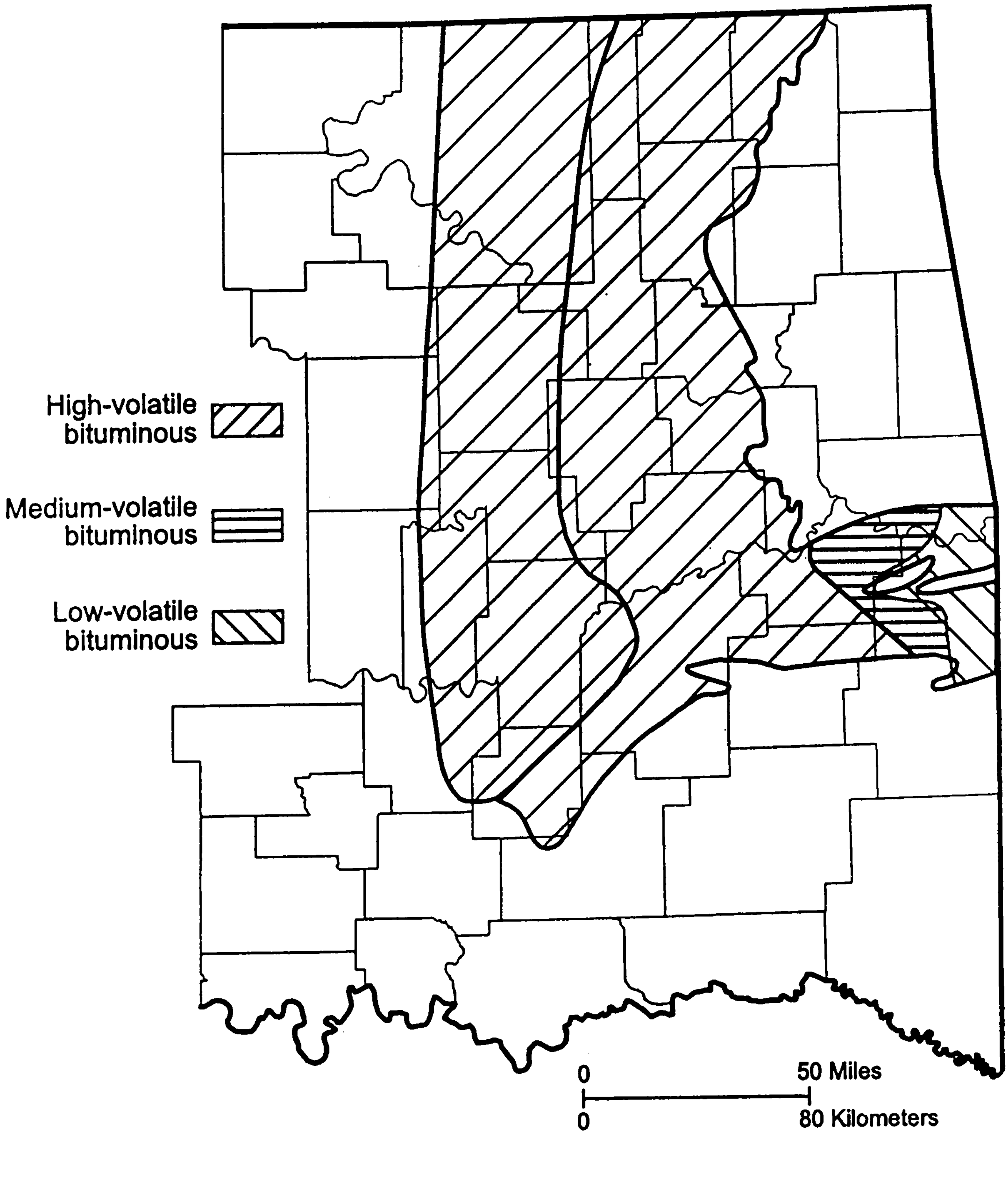


Generalized stratigraphic cross section, northern and southern Arkoma Basin.
(from Oklahoma Geological Survey Field Book 30, 1997, fig. 4)

ARKOMA BASIN
Major Structural Features



Structural features that influence stress and faulting in the Hartshorne formation. (modified from Hemish & Suneson, 1997, fig. 8)

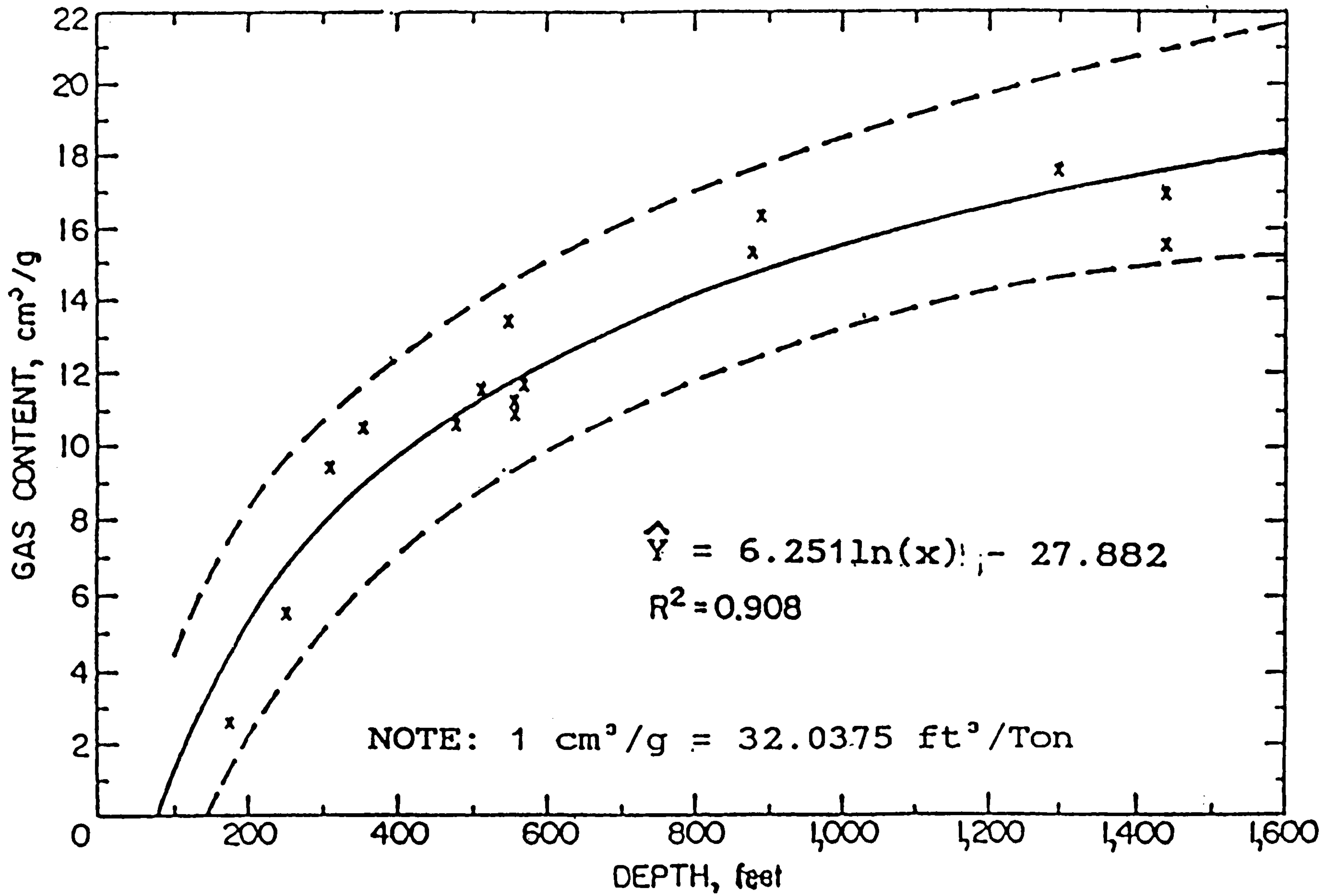

High-volatile bituminous
Medium-volatile bituminous
Low-volatile bituminous
0
50 Miles
0
80 Kilometers

PERMEABILITY

- CALCULATION METHODS
  - PUMP INJECTION-FALLOFF TESTS
  - TANK INJECTION W/BHP GAUGE
    OR FLUID LEVEL METER
  - REGRESSION OF FRAC-FALLOFF DATA
- RANGE OF VALUES & IMPLICATIONS
  - RECOVERY FACTOR-SPACING
  - PRODUCTIVE RATE
  - FRAC DESIGN

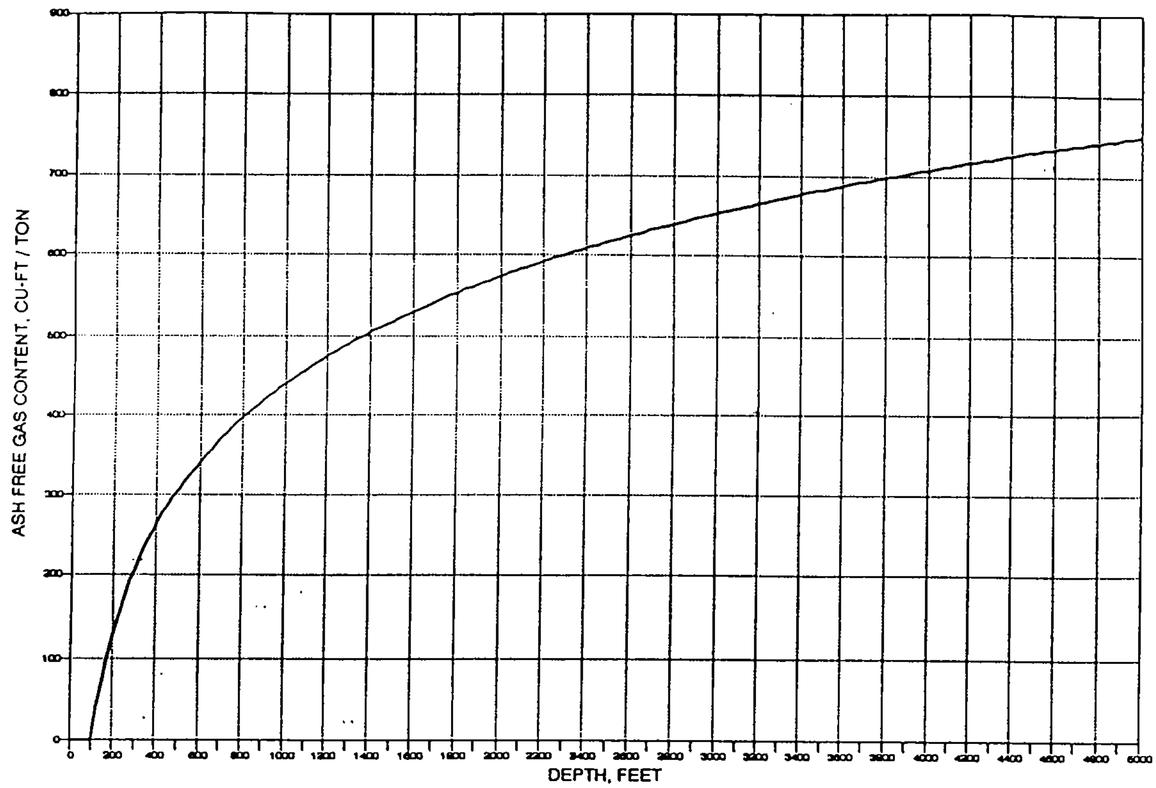
GAS CONTENT

- DESORPTION TESTS – Direct Measurement
  - BOM TEST OF 16 CORES
  - AZTEC CORE CAMERON AREA
  - KERR-McGEE TEST HASKELL CO
- CALCULATION OF GAS IN PLACE
  - CALCULATION METHODS
    - GIP = 1359.7 A h *pc* Gc
    - GIP = 1835 A h Gc (1-ash)
    - ANALYZING & DIGITIZING LOGS

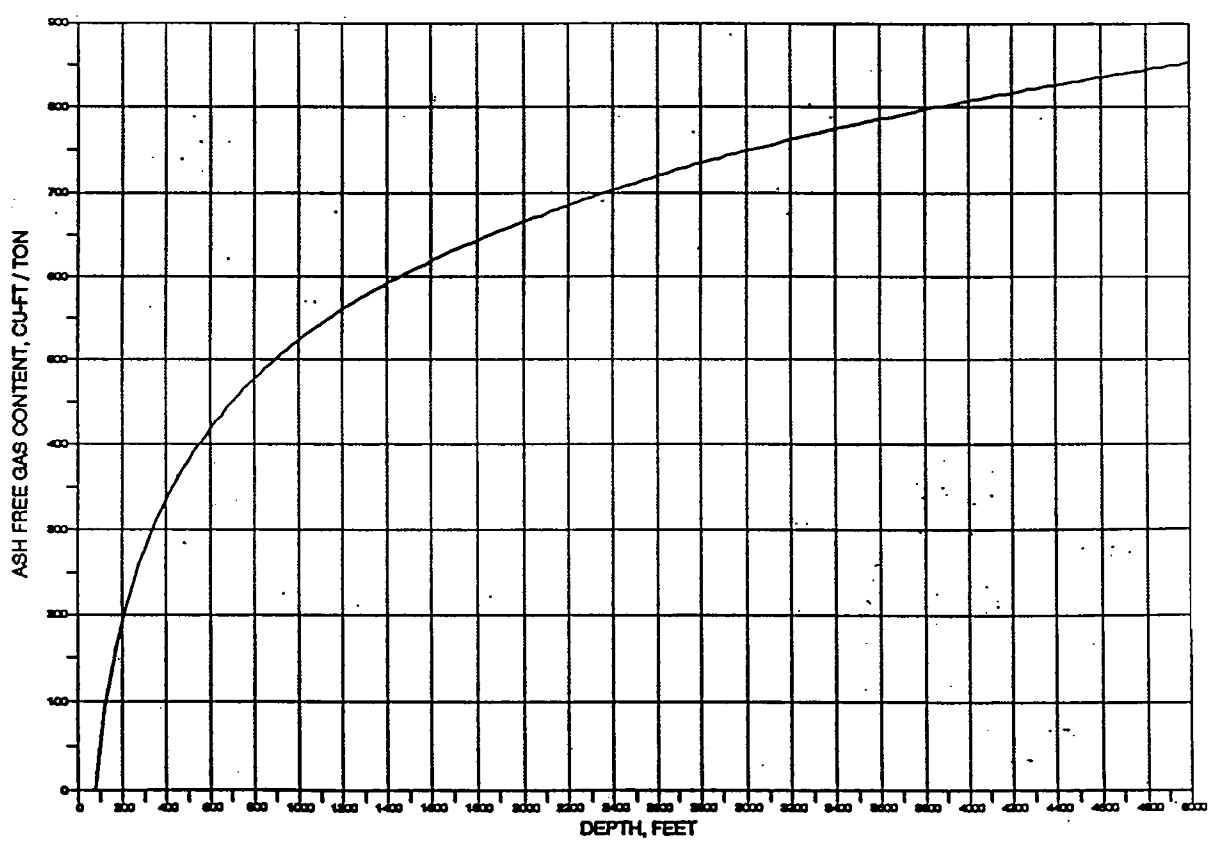


Desorbed gas content by Bureau of Mines on 16 Hartshorne Coal cores in Haskell & LeFlore Counties (from Iannacchione & Puglio USBOM, 1979)

KINTA AREA-HARTSHORNE COAL ISOTHERM
16 US BOM CORES-ADJUSTED TO .279 PSI/'



LeFLORE CO-HARTSHORNE COAL ISOTHERM
BASIS: 16 US BOM & 1 AZTEC CORES



CALCULATION OF RECOVERABLE GAS

- **DETERMINE Gc WITH BOM EQUATION:**
  - **Gc = 32.0375(6.252(lnDepth)-27.882)**
- **APPLY RECOVERY FACTOR**
  - **Fr = APPROX 65% FOR 25 md PERM**

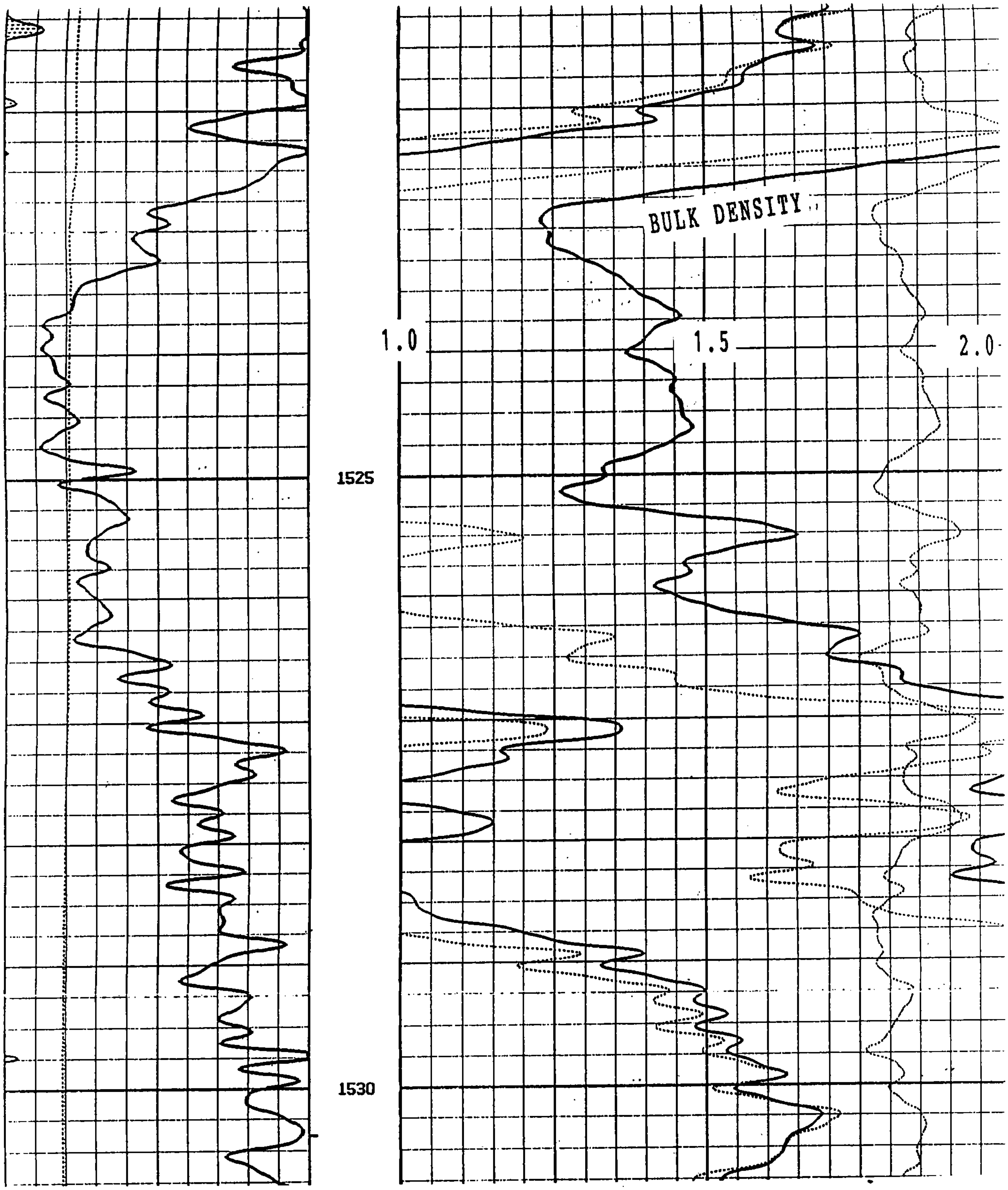
RECOVERABLE GAS (EXAMPLE)

- CALCULATED GAS FOR AN AVERAGE WELL
  - 1500 ft depth-hydrostatic gradient 0.33 psi/ft
  - 80 Acres drainage
  - 4.25’ thickness
  - 10% ash
  - 571 cubic feet/Ton Gas Content
  - 65% Recovery factor
  - Indicated reserves = 220,800 mcf

- ACTUAL RECOVERY EXPERIENCE (5-8 yrs)
  - 269,000 to 439,000 mcf from well performance
  - EXPECT 30-100% ABOVE CALCULATIONS
  - AGREES with multi-basin actual experience

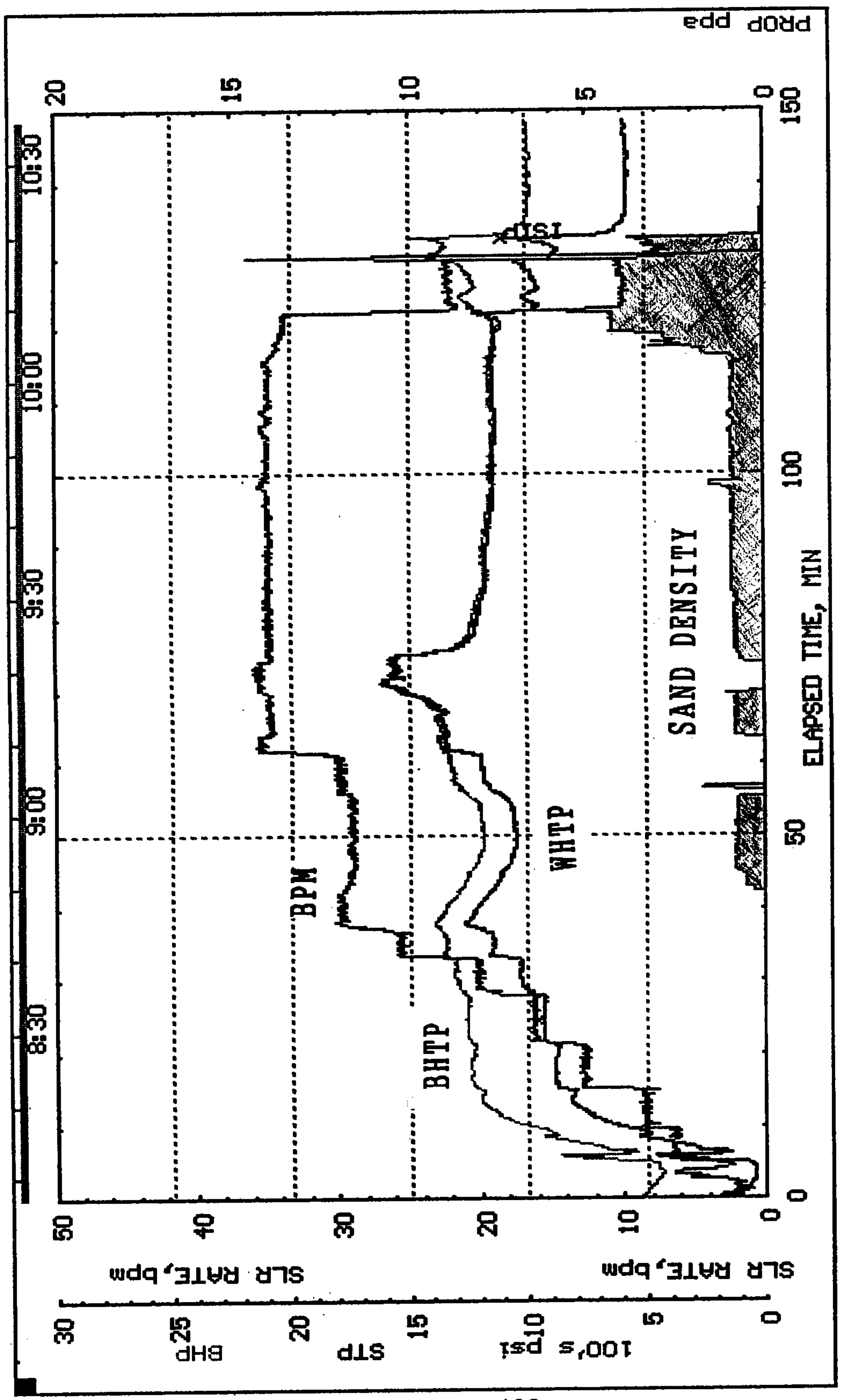
ARKOMA BASIN CBM PRACTICES

- GEOLOGY-RESEARCH-LOGS-LANDSAT
- DRILLING METHODS-LOGGING SUITES
  CASING PROGRAM & CEMENTING METHODS
  H2O DISPOSAL
- WELL STIMULATION PRACTICES & REFRACS
- PRODUCTION METHODS-GATHERING-PIPELINES
- DATA ACQUISITION
- WELL PRODUCTION PROFILES-ECONOMICS

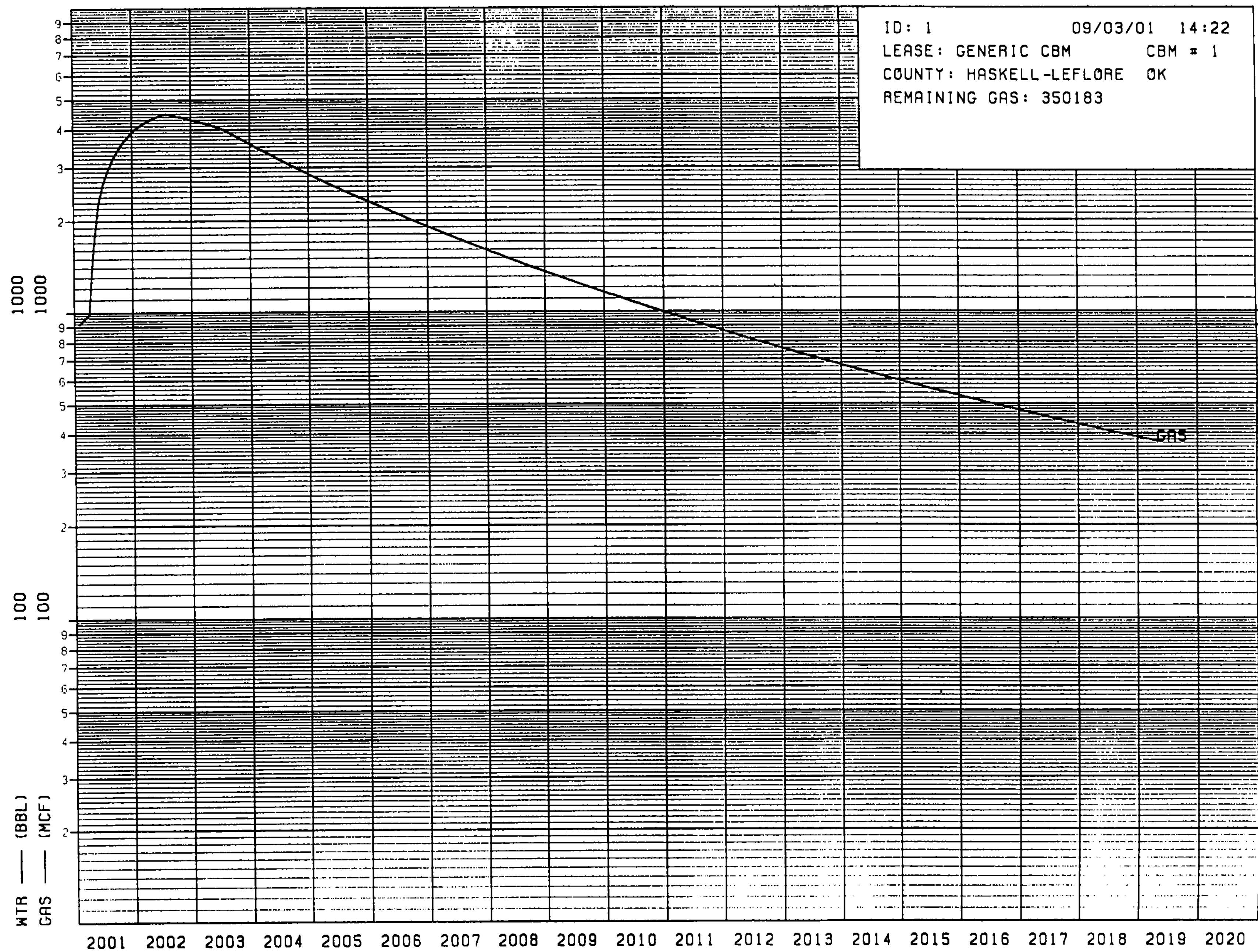


Density log from CBM well in LeFlore County-100 in scale, High Resolution.

Coal Seam
Water Sand Frac
4 1/2 Csg
PAGE : 1-G (8/23/2001 12:36:22) Data stored in DATADIR



Frac of 790 ft Hartshorne Coal with 131,000# 12/20 & 3,500 bbl of water.



Average production profile-based on 23 CBM wells in 3 section pod.

HARTSHORNE COALS 14:02

1500 FT PRODUCING ZONE -- ALL LEASES

YEAR	WELL CNT	GROSS PRODUCTION BBL OIL	GROSS PRODUCTION MCF GAS	NET PRODUCTION BBL OIL	NET PRODUCTION MCF GAS	PRICE OIL	PRICE GAS	SALES INCOME OIL $	SALES INCOME GAS $	SALES INCOME TOTAL $
2001	1	0	30,169	0	24,135	0.00	3.000	0	72,405	72,405
2002	1	0	51,976	0	41,581	0.00	3.041	0	126,468	126,468
2003	1	0	47,459	0	37,968	0.00	3.131	0	118,868	118,868
2004	1	0	37,949	0	30,359	0.00	3.224	0	97,891	97,891
2005	1	0	30,523	0	24,419	0.00	3.321	0	81,102	81,102
2006	1	0	24,984	0	19,987	0.00	3.421	0	68,377	68,377
2007	1	0	20,756	0	16,605	0.00	3.524	0	58,513	58,513
2008	1	0	17,466	0	13,973	0.00	3.630	0	50,718	50,718
2009	1	0	14,863	0	11,890	0.00	3.739	0	44,454	44,454
2010	1	0	12,772	0	10,218	0.00	3.851	0	39,348	39,348
2011	1	0	11,071	0	8,857	0.00	3.967	0	35,131	35,131
2012	1	0	9,671	0	7,737	0.00	4.086	0	31,611	31,611
2013	1	0	8,507	0	6,806	0.00	4.208	0	28,640	28,640
2014	1	0	7,530	0	6,024	0.00	4.335	0	26,113	26,113
2015	1	0	6,704	0	5,363	0.00	4.465	0	23,943	23,943
2019	1	0	17,781	0	14,225	0.00	4.750	0	67,560	67,560
TOT		0	350,183	0	280,146	0.00	3.467	0	971,143	971,143

YEAR	EXPENSES TAXES	EXPENSES MKTG	EXPENSES OPER	EXPENSES TOTAL	NET OPER INCOME	OTHER COSTS	NET CASH FLOW ANNUAL	NET CASH FLOW CUMULATIVE	10.00 PCNT DISCOUNTED	
2001	7,168	6,034	9,000	22,202	50,203	95,000 C	-44,797	-44,797	-47,212	-47,212
2002	12,520	10,395	9,123	32,039	94,429	0	94,429	49,632	81,493	34,281
2003	11,768	9,492	9,397	30,657	88,212	0	88,212	137,844	69,358	103,639
2004	9,691	7,590	9,679	26,960	70,931	0	70,931	208,775	50,719	154,358
2005	8,029	6,105	9,969	24,103	56,999	0	56,999	265,775	37,048	191,406
2006	6,769	4,997	10,268	22,034	46,343	0	46,343	312,118	27,381	218,788
2007	5,793	4,151	10,576	20,520	37,993	0	37,993	350,111	20,406	239,194
2008	5,021	3,493	10,893	19,408	31,310	0	31,310	381,421	15,287	254,481
2009	4,401	2,973	11,220	18,594	25,860	0	25,860	407,281	11,479	265,960
2010	3,895	2,554	11,557	18,007	21,341	0	21,341	428,622	8,612	274,571
2011	3,478	2,214	11,904	17,596	17,536	0	17,536	446,158	6,433	281,004
2012	3,129	1,934	12,261	17,324	14,286	0	14,286	460,444	4,765	285,769
2013	2,835	1,701	12,628	17,165	11,475	0	11,475	471,919	3,480	289,249
2014	2,585	1,506	13,007	17,099	9,014	0	9,014	480,933	2,486	291,735
2015	2,370	1,341	13,398	17,109	6,835	0	6,835	487,768	1,714	293,449
2019	6,688	3,556	47,630	57,874	9,686	0	9,686	497,453	2,078	295,527
TOT	96,143	70,037	212,510	378,690	592,453	95,000	497,453	497,453	295,527	295,527

PCNT DSCNT	$ VALUE
0.00	497,453
10.00	295,527
15.00	236,862
20.00	193,136
25.00	159,468
30.00	132,844
35.00	111,318
40.00	93,589
50.00	66,185
75.00	24,350
100.00	1,031

ROR: > 100.00 IROI: 5.24
PAYOUT: 1.50 EROI: 6.24
1500 FT W/600 CU-FT/T, 80 AC, 6.0' 360,000 MCF RECOVERABLE

	BBL OIL	MCF GAS
ULTIMATE GROSS	0	350,183
CUM PROD GROSS	0	0
FUTURE RES GROSS	0	350,183
FUTURE RES NET	0	280,146
GROSS WELL COUNT	0.000	1.000
NET WELL COUNT	0.000	1.000

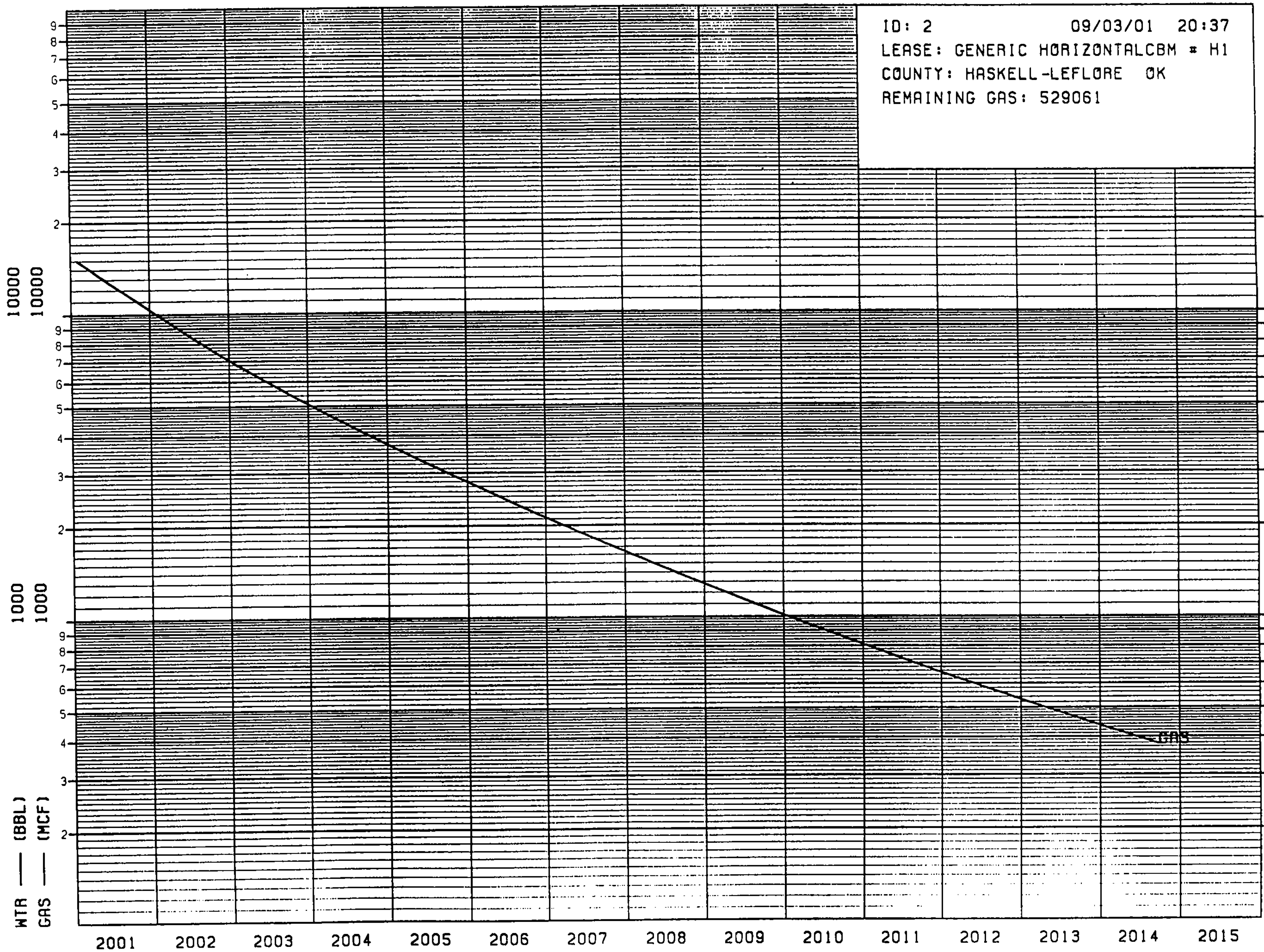
INTERESTS

YR	MO	OILINT	GASINT	WORKINT	TANGINT	INTANGINT
1	1	0.800000	0.800000	1.000000	1.000000	1.000000

PREPARED BY: WENDELL CONSULTING, LLC

EFFECTIVE DATE: 1 JANUARY 2001
LEASE ID: 1
LEASE NAME: GENERIC CBM
WELL NAME: CBM # 1
STATE: OKLAHOMA
COUNTY: HASKELL-LeFLORE
FIELD: ARKOMA HARTSHORNE CBM
OPERATOR: WENDELL CONSULTING, LLC
RES CAT: PROBABLE UNDEVELOPED NONPRODUCING
ECON LIMIT: 1904

Average economic profile-based on 23 CBM wells in 3 section pod.



Actual Horizontal production profile-Offsets 23 CBM wells in 3 section pod.

ARKOMA BASIN CBM PROJECT
HARTSHORNE COALS
1500 FT PRODUCING ZONE -- ALL LEASES

09/03/01
20:52

	WELL	GROSS PRODUCTION		NET PRODUCTION		PRICE		SALES INCOME		
YEAR	CNT	BBL OIL	MCF GAS	BBL OIL	MCF GAS	OIL	GAS	OIL $	GAS $	TOTAL $
2001	1	0	149,918	0	119,935	0.00	3.000	0	359,804	359,804
2002	1	0	100,924	0	80,739	0.00	3.038	0	245,299	245,299
2003	1	0	70,779	0	56,623	0.00	3.130	0	177,218	177,218
2004	1	0	51,570	0	41,256	0.00	3.224	0	133,002	133,002
2005	1	0	38,291	0	30,633	0.00	3.321	0	101,722	101,722
2006	1	0	28,912	0	23,129	0.00	3.420	0	79,113	79,113
2007	1	0	22,159	0	17,727	0.00	3.523	0	62,457	62,457
2008	1	0	17,214	0	13,771	0.00	3.629	0	49,975	49,975
2009	1	0	13,536	0	10,829	0.00	3.738	0	40,477	40,477
2010	1	0	10,762	0	8,609	0.00	3.850	0	33,148	33,148
2011	1	0	8,643	0	6,914	0.00	3.966	0	27,421	27,421
2012	1	0	7,005	0	5,604	0.00	4.085	0	22,893	22,893
2013	1	0	5,727	0	4,581	0.00	4.207	0	19,275	19,275
2014	1	0	3,621	0	2,897	0.00	4.319	0	12,509	12,509
TOT		0	529,061	0	423,249	0.00	3.223	0	1,364,312	1,364,312

	EXPENSES				NET	OTHER	NET CASH FLOW			
YEAR	TAXES	MKTG	OPER	TOTAL	OPER INCOME	COSTS	ANNUAL	CUMULATIVE	10.00 PCNT DISCOUNTED	
2001	35,621	29,984	9,000	74,604	285,200	300,000 C	-14,800	-14,800	-25,784	-25,784
2002	24,285	20,185	9,123	53,592	191,706	0	191,706	176,906	166,055	140,271
2003	17,545	14,156	9,397	41,097	136,121	0	136,121	313,027	107,143	247,414
2004	13,167	10,314	9,679	33,160	99,842	0	99,842	412,869	71,436	318,850
2005	10,070	7,658	9,969	27,698	74,024	0	74,024	486,893	48,145	366,995
2006	7,832	5,782	10,268	23,883	55,230	0	55,230	542,123	32,655	399,650
2007	6,183	4,432	10,576	21,191	41,265	0	41,265	583,388	22,181	421,830
2008	4,948	3,443	10,893	19,284	30,691	0	30,691	614,079	14,998	436,828
2009	4,007	2,707	11,220	17,935	22,542	0	22,542	636,622	10,016	446,844
2010	3,282	2,152	11,557	16,991	16,157	0	16,157	652,779	6,528	453,372
2011	2,715	1,729	11,904	16,347	11,074	0	11,074	663,853	4,069	457,441
2012	2,266	1,401	12,261	15,928	6,965	0	6,965	670,817	2,329	459,770
2013	1,908	1,145	12,628	15,682	3,593	0	3,593	674,411	1,095	460,865
2014	1,238	724	9,719	11,682	827	0	827	675,238	233	461,098
TOT	135,067	105,812	148,195	389,074	975,238	300,000	675,238	675,238	461,098	461,098

PCNT DSCNT	$ VALUE
0.00	675,238
10.00	461,098
15.00	389,844
20.00	333,174
25.00	287,115
30.00	248,985
35.00	216,921
40.00	189,590
50.00	145,484
75.00	72,781
100.00	28,459

ROR: > 100.00 IROI: 2.25
PAYOUT: 1.08 EROI: 3.25
1500FT HORIZONTAL-6'-1800FT HORIZONTAL LEG-529 MMCF RECOVERABLE

	BBL OIL	MCF GAS
ULTIMATE GROSS	0	529,061
CUM PROD GROSS	0	0
FUTURE RES GROSS	0	529,061
FUTURE RES NET	0	423,249
GROSS WELL COUNT	0.000	1.000
NET WELL COUNT	0.000	1.000

INTERESTS

YR	MO	OILINT	GASINT	WORKINT	TANGINT	INTANGINT
1	1	0.800000	0.800000	1.000000	1.000000	1.000000

PREPARED BY: WENDELL CONSULTING, LLC

EFFECTIVE DATE: 1 JANUARY 2001
LEASE ID: 2
LEASE NAME: GENERIC HORIZONTAL CBM
WELL NAME: CBM # H1
STATE: OKLAHOMA
COUNTY: HASKELL-LeFLORE
FIELD: ARKOMA HARTSHORNE CBM
OPERATOR: WENDELL CONSULTING, LLC
RES CAT: PROBABLE UNDEVELOPED NONPRODUCING
ECON LIMIT: 1409

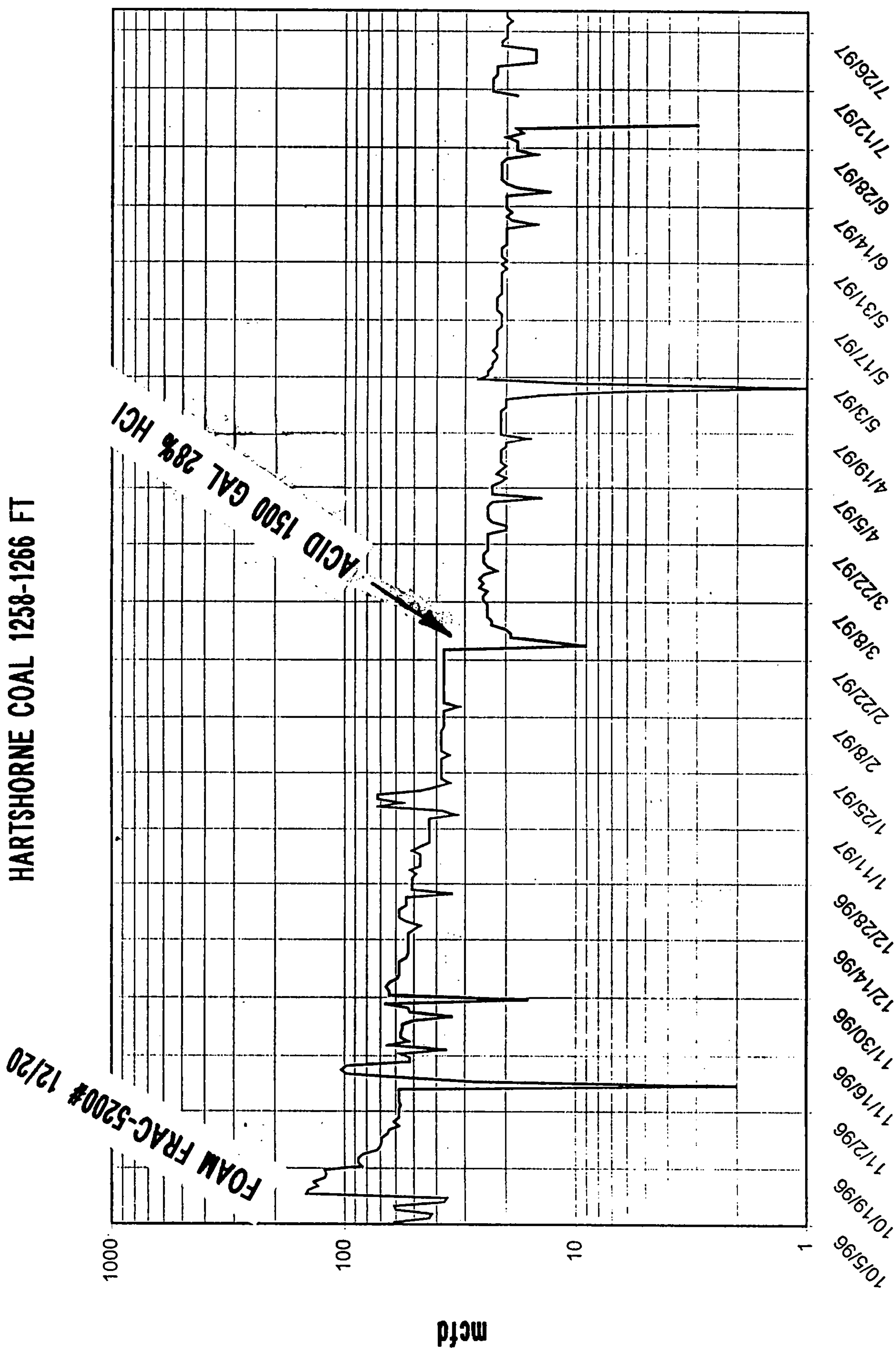
Projected economic profile for Horizontal well-Offsets 23 Vertical CBM wells.

LESSONS LEARNED

PROTECT PERMEABILITY-PROTECT PERMEABILITY

- FRAC DESIGN AND PERFORMANCE

- DETRIMENTAL SUBSTANCES
  - ACIDS
  - XYLENE-TOLUENE
  - GASOLINE-BENZINE-DIESEL
  - CONDENSATE-STRONG SOLVENTS
  - BLEACH
  - GELS
  - FOAMS
  - STRONG SURFACTANTS-FOAMERS
  - 100 MESH SAND


HARTSHORNE COAL 1258-1266 FT
FOAM FRAC-5200# 12/20
ACID 1500 GAL 28% HCl
mcfd
1000
100
10
1
10/5/96
10/19/96
11/2/96
11/16/96
11/30/96
12/14/96
12/28/96
1/11/97
1/25/97
2/8/97
2/22/97
3/8/97
3/22/97
4/5/97
4/19/97
5/3/97
5/17/97
5/31/97
6/14/97
6/28/97
7/12/97
7/26/97

LESSONS LEARNED (Continued)

- FINES PLUGGING
  - CAUSED BY STIMULATION
  - RELEASED BY CHEMICAL ACTION
  - MIGRATED-POOR PRODUCTION PRACTICES
- MINERALIZATION
  - TYPES
  - CAUSES
  - REMEDIES
- KEEP WELLS PUMPING AND IN GOOD REPAIR

PROTECT PERMEABILITY

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

7

Midcontinent evolving coalbed-methane completion techniques and practices

Roger Marshall
Cudd Pumping Services
Seminole, OK

Marshall, R., 2001, Midcontinent evolving coalbed-methane completion techniques and practices, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 140-150.

Drilling and Completion Considerations

Open Hole Completion

Advantages

- Reduces damage from drilling fluids and cement

Disadvantages

- Tendency to produce coal fines and frac sand
- Difficult to control frac due to excess exposure of other formations
- Limited amount of rathole for pump placement

Hole Size

6 ¼ inch

Advantages

- Cheaper to drill
- Less cement required

Disadvantages

- Difficult to centralize casing
- Increased potential for bridging
- Higher annular friction increases risk of cement invasion in coals
- More costly cements required to reduce friction and limit invasion

7 7/8 inch

Advantages

- Better casing centralization
- Larger casing (5 ½")can be used if necessary
- Reduced potential for bridging in annulus
- Lower annular friction reduces potential for cement invasion
- More options available for cement design

Disadvantages

- Increased drilling costs
- Larger volumes of cement required

Drilling and Completion Considerations (continued)

Cementing & Perforating

- Extremely critical to success of well
- 2 sks cement can fill cleats in 4 ft coal to radius of 5 ft
- Use best available cement and procedure to. reduce damage

- Perforate with 4 to 6 spf using scallop gun or slick gun.
- More research needed regarding orientation of perforations with cleats.

After drilling

- TD well and trip out of hole
- Only load hole if sand or other formation warrants need for induction log. Only interested in bulk density log. Run high resolution if available.
- If needed load with KCl water
- Do not use gel or mud

Early Observations

- 63 wells were fraced without a screenout
- High frac gradients
  - FG averaged 1.55 psi/ft with some as high as 2.0 psi/ft. Researchers indicated that this trend was normal in coals due to multiple fractures and multiple orientations although most wells did have a FG of less than 1.0 psi/ft early in treatment. Explanation was that obtained rates were not high enough at that point in the treatment to initiate a true fracture.
- Wells produced a tremendous volume of coal fines. Found to be detrimental to downhole pumps.
- 50% of gas production would typically be lost after pump changes. Water rates would only drop 5 to 10%.

Early Conclusions

- Coal fine plugging was responsible for high decline rates and poor production.
- The combination of high water and gas rates were thought to provide the mechanism for fines transport.
- Backpressure was held in attempt to control fines movement but success was limited.

Early Solutions

"Eliminate the fines, eliminate the problem."

- Fines were assumed to be created from proppant etching of the coal face.
- Observations from Stim-Lab indicated that fines are created by the turbulence of the fluid within the fracture. Foams and gels have a velocity of zero at the coal face.
- Recommended that linear foam with minimal foamer be used.
- Treatments were total failures

Development and Modification of Controlled Velocity Frac

- Wilkins observed that frac gradients from foam and gel fracs were considerably lower than those from water fracs and suspected that fracs were growing out of the coal.

- Later, tagged sand confirmed frac heights of 45' and 72' into the unproductive Hartshorne Sand.

- Flowbacks during two fracs also yielded "coal slurry" indicating excessive turbulence in the fracture.

- During review of frac charts, Wilkins found that the point of coal failure was typically 20 bpm in a 5 ½ ft. coal or 3.5 bpm per foot of coal.

  - Later observations in thinner coal bodies indicate that failure can occur at rates as low as 2 to 2 ½ bpm/ft.

  - Low concentrations of friction reducers and sand appear to reduce turbulence allowing higher pump rates without increasing damage to coal.

- Wilkins then developed the theory that a "critical velocity" is reached during treatment, producing coal fines resulting in screen-out or diversion out of the coal.

- Since proppant transport is difficult at lower rates, a method to decrease the velocity had to be developed.

  - Research into thin fluid proppant transport indicates that high velocity is not as important as it was once thought to be. Field tests have confirmed that considerable amounts of sand can be placed at much lower pumping rates

- Increased fracture width would ultimately decrease the velocity within the fracture

- Fracture width can usually be increased by increasing the fluid viscosity with gels, but gels tend to produce severe damage in most coals.

Development and Modification of Controlled Velocity Frac (continued)

- The "Controlled Velocity Frac" was then developed utilizing 100 mesh sand to increase fluid efficiency.
  - Recent field tests indicate that 100 mesh sand is not always necessary to control. leakoff and in many cases can be eliminated or replaced with larger sand
- Dramatic decreases in frac gradients were noted on initial treatments.
- Further refinements made by running sand continuously, and controlling reduction of pump rates and rate surges during gear changes.
  - Observations indicate that changes in pumping rate are extremely critical. In some cases even when rate changes are small (±1 bpm) and performed smoothly dramatic increases in pressure can occur.
- Indications of limited entry into perforations from studies from the Black Warrior and confirmed by downhole camera lead to the adoption of acid spearhead. Although damaging to the coal, the immediate succession of water will dilute the acid to the point of no damage, except maybe near wellbore.

Introduction To NE Oklahoma – 1999-2000

- Typical treatments consisted of 400 bbl 10# to 30# gel with 8,000# to 12,000# proppant.

Multiple screen-outs noted and frac gradients ranging from 1.6 psi/ft to 3.0 psi/ft.

- Good rates noted during drilling operations, but very poor production after fracs.
- Downsized "controlled velocity" treatment to match coal thickness.
- Dramatic decrease in frac gradients and increase in gas and water rates.
- Failed frac attempt resulted in the discovery of the acid/water treatment and true nature of permeability.

1999-2000 Completion Procedure

1. Swab well down.
2. Start acid & load hole.
3. Breakdown formation @ <3 bpm.
4. Pump ½ volume of acid through perforations.
5. Shut down. Soak acid for 5 minutes
6. Resume pumping @ 5 bpm.
7. Increase rate in 2 bpm increments every 30 to 50 bbl if pressure is stable or falling. Hold rate if pressure is increasing after 30 bbl.
8. Limit maximum rate to 3.5 times coal thickness.
9. Shut well in for minimum of 48 hrs.
10. Run tubing, pump and rods.
11. Test well. It is not necessary to hold back pressure to restrict gas volume.
12. If needed frac well with controlled velocity frac treatment minus acid spearhead.

Typical Acid Procedure

Rowe Coal
Thickness – 3 ½ ft
Depth - ±1000 ft.

1. Run open ended tubing to below perforations
2. Pump 1 bbl acid down tubing and out annulus into bobtail
3. Spot remaining acid across perforations
4. Shut in annulus and chain tubing down
5. Break down formation at 3 bpm or less
6. Pump approximately half of the designed acid volume at breakdown rate (<3 bpm)
7. Increase pump rate to ±4 bpm
8. Increase pump rate in 1 to 2 bpm increments every 25 to 30 bbls if pressure is stable or decreasing. Do not increase pump rate if pressure is increasing after 30 bbls of displacement.
9. Limit maximum rate to 2 ½ times coal thickness
10. Shut well in and allow to go on vacuum. Bleed pressure off slowly if still holding pressure after 24 hours.
11. Run tubing, pump and rods.
12. Test well holding back pressure to maximize water recovery and prevent premature gas breakthrough unless field experience in the area indicates it is not necessary
13. If needed frac well with Controlled Velocity Frac treatment

750 gallons 15% HCl with 1gpt corrosion inhibitor
240 bbls fresh water with biocide

Typical Controlled Velocity Frac Treatment

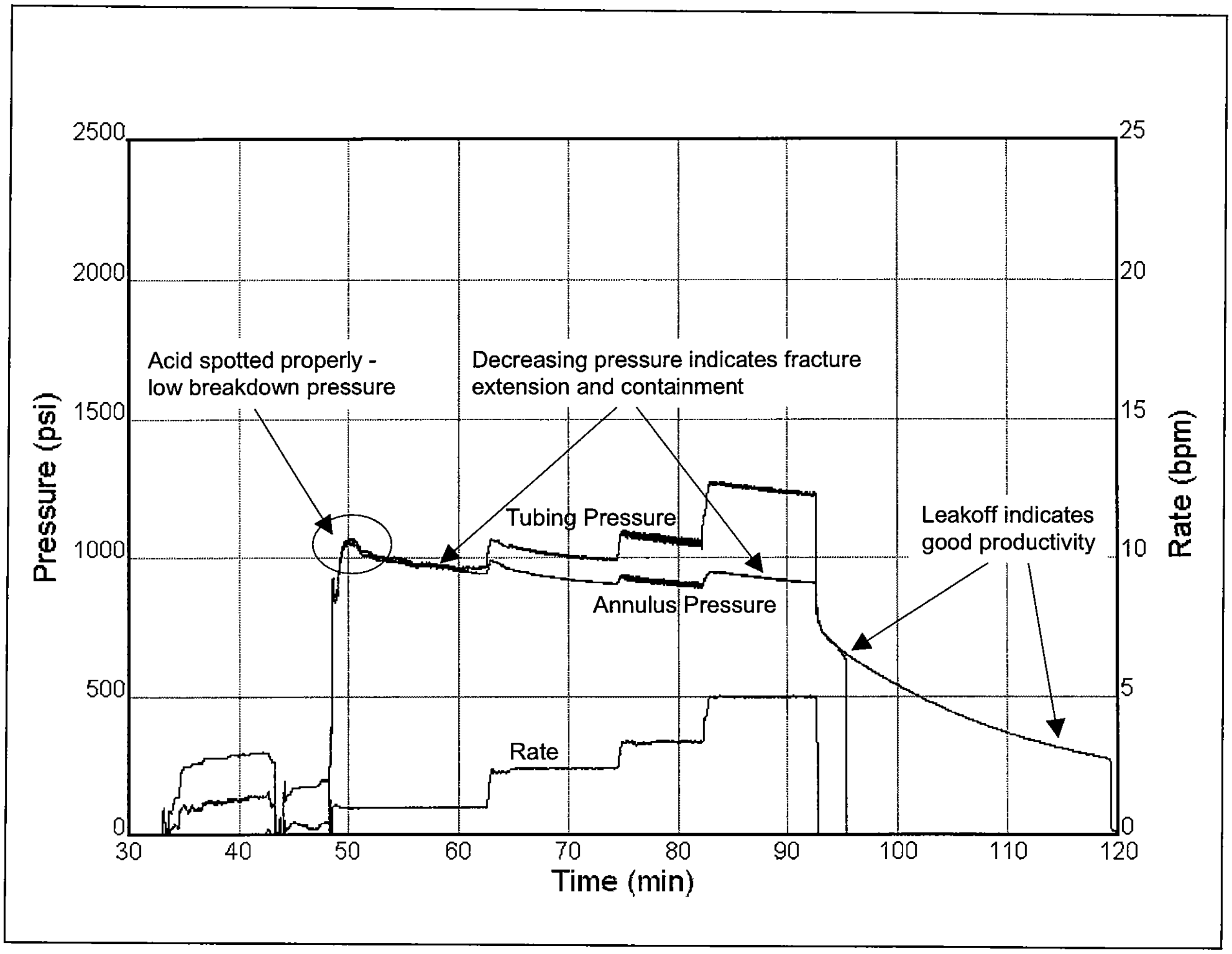
Hartshorne Coal
Thickness - 6 ft.
Depth - ±1500 ft.

1. 180 bbls Pad at 4 – 10 bpm
2. 180 bbls Pad at 12 – 14 bpm
3. 180 bbls Pad at 16 – 18 bpm
4. 80 bbls with ¼ ppg 100 mesh sand at 20 – 22 bpm
5. 80 bbls with ½ ppg 100 mesh sand at 22 bpm
6. 80 bbls with ¾ ppg 100 mesh sand at 24 bpm
7. 80 bbls with 1 ppg 100 mesh sand at 24 bpm
8. 220 bbls with 1 ppg 20/40 sand at 24 bpm
9. 220 bbls with 1 ½ ppg 20/40 sand at 24 bpm
10. 230 bbls with 1 ppg 12/20 sand at 24 bpm
11. 150 bbls with 2 ppg 12/20 sand at 24 bpm
12. ±30 bbls Flush
14. Shut well in and allow to go on vacuum. Bleed pressure off slowly if still holding pressure after 24 hours. Flowback rate should be limited to 2 bbls per hour or less
15. Run tubing, pump and rods.
16. Test well holding back pressure to maximize water recovery and prevent premature gas breakthrough unless field experience in the area indicates it is not necessary

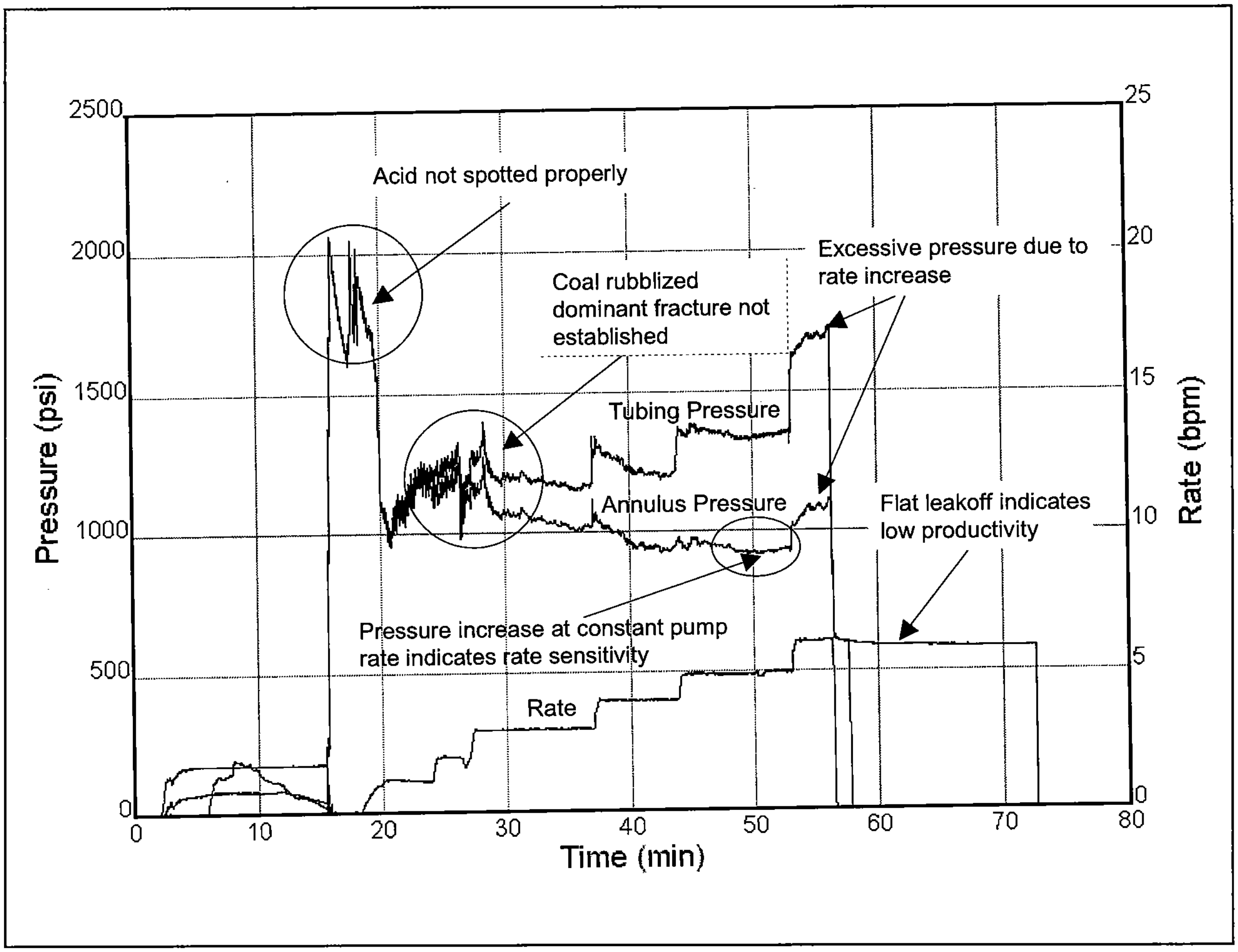
1710 bbls fresh water with biocide and ¼ gpt friction reducer
8,400 lbs 100 mesh sand
23,100 lbs 20/40 mesh sand
22,300 lbs 12/20 mesh sand

Summary

- Cased hole completions are preferred due to improved zonal isolation and fewer production problems
- Larger hole size reduces damage due to cementing and allows more flexibility in completions
- The generation of coal fines is a major cause of stimulation failures and resulting low productivity
- The generation of coal fines can be minimized by using proper stimulation techniques and production practices
- Fracturing gels and most other conventional stimulation additives have generally proven to be detrimental to production of coal bed methane
- In Eastern Kansas, Western Arkansas and all of Eastern Oklahoma, fresh water with a biocide and a minimal amount of friction reducer has proven to be the least damaging fracturing fluid in most cases
- Although hydrochloric acid can be damaging to most coals, small volumes of acid can provide definite benefits when applied properly
- Fracturing procedures are continually being modified and improved as more experience is gained in the Mid-Continent area. Current treatment trends are toward lower pumping rates, less 100 mesh and 20/40 sand and more 12/20 sand
- Proper production practices are at least as important as drilling and completion practices in coal bed methane wells



2500
2000
1500
1000
500
0
Pressure (psi)
25
20
15
10
5
0
Rate (bpm)
30
40
50
60
70
80
90
100
110
120
Time (min)
Acid spotted properly - low breakdown pressure
Decreasing pressure indicates fracture extension and containment
Tubing Pressure
Annulus Pressure
Leakoff indicates good productivity
Rate



2500
2000
1500
1000
500
0
Pressure (psi)
25
20
15
10
5
0
Rate (bpm)
0
10
20
30
40
50
60
70
80
Time (min)
Acid not spotted properly
Coal rubblized dominant fracture not established
Excessive pressure due to rate increase
Tubing Pressure
Annulus Pressure
Flat leakoff indicates low productivity
Pressure increase at constant pump rate indicates rate sensitivity
Rate

OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 2-2001

8

Arkoma basin coalbed methane: Overview and discussion of successes and failures

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O'Connor, D., 2001, Arkoma basin coalbed methane: Overview and discussion of successes and failures, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, p. 151.

Arkoma Basin Coalbed Methane:
Overview and Discussion of Successes and Failures

Doug O'Connor
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Things to think about

Permeability, permeability, permeability

Tensional geologic features enhance permeability

Temperature logs and gas shows reported on driller's logs are obvious indications of permeability

Sandstones are still our friends

Gas-in-place does not make you as much money as gas that is sold

Lateral variations in coal character are much more extreme than logs indicate

The most important contour on the coal isopach is the zero line

Air drilling is a godsend

Examine the cleat structure in a coal hand sample. The black stuff on your hands is called "coal fines". This stuff is not your friend.

Determine coal thickness from the gamma ray, not the density

Completion techniques ???

Whoever coined the phrase "you can't screw up a good well" was not the prospect generator

After the bit penetrates the coal there are many more ways to hurt the coal than help it

Be patient

Why are coals notorious for drinking cement but the fracture gradient is so high?

Is there really twice as much gas-in-place in a coal with a density of 2 g/cm^3 vs one with a density of 1 g/cm^3 when all other attributes are identical?

Are there any good prospects left?

9

Appendix

Sisson, N.S., 2001, Hartshorne coalbed-methane economics in Oklahoma, *in* Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey, Open-File Report 2-2001, 8 p. (Presented at Oklahoma Coalbed-Methane Workshop in Oklahoma City, March 29, 2001)

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Hartshorne Coalbed-Methane Economics in Oklahoma

Presented March 29, 2001

S. Neil Sisson
Wildhorse Operating Company
President

LEASEHOLD COST CONSIDERATIONS

1) Land Intensive Area – High Brokerage Costs
    a) On Structure – Lots of HBP Acreage
        1) Working Under Old JOA's
        2) Usually Spaced 640's
        3) Dealing With Major Companies or Large Independents
            A) Farmouts - 75% NRI With Possible BIAPO
            B) Term Lease - $100 to $300 per Acre for Shallow Rights
            C) Prolonged Procedure
    b) Off Structure – Non HBP
        1) Minerals Broken up Small Tracts
        2) Sophisticated Mineral Owner
        3) Knowledgeable Landowners
            A) Costs for Pipeline Right-of-Way
            B) Surface Damages
    c) Pool & Space
        1) Prepare Up Front for Increased Well Density and Locations
            A) Attorney - Corporation Commission Work
            B) Engineer – Technical Witness
            C) Geologist - Technical Witness
    d) Check out Surface of the Ground
        1) Topographic Maps Do Not Tell Story of Some Creek Depths and Some Hill Inclines

AVERAGE WELL COST

BASED ON FOUR WELLS DRILLED JANUARY THRU OCTOBER, 2000
856' AVERAGE DEPTH

INTANGIBLE DRILLING & COMPLETION COSTS

SURVEYOR & PERMITS	$575.00
SURFACE DAMAGE	$1,800.00
LOCATION ROADS & PITS	$3,800.00
DRILLING FOOTAGE	$4,600.00
DRILLING DAYWORK	$500.00
OPEN HOLE LOGS	$1,100.00
WATER TO DRILL & CEMENT	$420.00
SUPERVISION ENGINEERING	$700.00
SUPERVISION EXPENSE	$500.00
DRILLING OVERHEAD	$375.00
CASED HOLE LOGS & PERFORATING	$2,550.00
CEMENT (To Surface)	$3,600.00
COMPLETION UNIT	$870.00
STIMULATION ACID WATER	$2,900.00
TANK BATTERY CONSTRUCTION	$950.00
	$25,240.00

EQUIPMENT COSTS (Flowing Well)

CONDUCTOR CASING (1JT.)	$240.00
PRODUCTION CASING	$2,200.00
TUBING	$1,600.00
WELLHEADS	$550.00
STOCK TANK	$1,100.00
CONNECTIONS	$1,000.00
GAS SEPARATOR	$1,100.00
	$7,790.00
TOTAL	$44,670.00

NOTE ADDITIONAL COSTS

PUMPING WELL	$10,000.00
FRAC JOB	$30,000.00

LEASE OPERATING EXPENSES

	Flowing Well		Pumping Well
Pumper	$150		$ 175
Overhead	$250	($125 each additional well on lease)	$ 250
Revenue Distribution	$ 50		$ 50
Insurance	$ 20		$ 20
Soap	$ 30		$ 0
Maintenance & Misc.	$ 50		$ 50
Electricity	$ 0		$ 60
Pulling Expense (1)			$ 300
Water Hauling (2)	$100		$ 100
TOTAL	$650		$1005

(1) Assume 1 pump change per year;
Pump $1,800, Rig ¾ day $1500, Truck $300 = $3,500 /12 mths = $291

(2) Assume Mature Well 1 to 3 BWPD, $200 per 120 BBL Load

(3) Above example assume compression & gathering netted from gas revenues. Compression cost on a per well basis depends on number of wells put through the gathering point and the size of compressor needed for gas volume and discharge pressure.

REVENUE ANALYSIS AND TIMING

	WELL #1	WELL #2
DATE DRILLED	Jan-00	Apr-00
INITIAL PRODUCTION DATE	Mar-00	May-00
AMOUNT	30 mcfpd	10 mcfpd
30 DAY PRODUCTION	100 mcfpd	Loaded Up w/Water
TREATMENT	Acid/Water	Screened out Foam Frac
LEASEHOLD COSTS	$14,415	$0
WELL COST	$36,730	$43,776
LOES	$6,414	$3,257
TOTAL COSTS	$57,559	$47,033
REVENUES Net to WI After Tax, 75 NRI and Gathering	$88,452	NA
PAYOUT	9 Months	Well was SI waiting on electric line, pumping unit & workover rig to run rods & pump.
CURRENT PROD.	92 mcfpd/0 BW	38 mcfpd/10 BWPD Put on Pump 03/01/01 Water Decreasing Gas Increasing

REVENUE ANALYSIS AND TIMING

	WELL #3	WELL #4
DATE DRILLED	Jul-00	Oct-00
INITIAL PRODUCTION DATE	Oct-00	Mar-01
AMOUNT	25 mcfpd	12 mcfpd
30 DAY PRODUCTION	50 mcfpd	NA
TREATMENT	Acid/Water	Acid/Water
LEASEHOLD COSTS	$0	$0
WELL COST	$34,340	$42,512
LOES	$3,658	$1,273
TOTAL COSTS	$37,998	$43,785
REVENUES Net to WI After Tax, 75 NRI and Gathering	$30,428	NA
PAYOUT	Next Month	Needs Frac
CURRENT PROD.	66 mcfpd/0 BW	21 mcfpd/0 BW

GAS GATHERING DEALS

1) Major Pipeline Markets

   a) ONEOK - 300 to 400 PSI Line Pressure

   b) ENOGEX - 50 to 80 PSI Line Pressure

   c) RELIANT - 50 to 150 PSI Line Pressure

   You Lay Gathering Line to Them and Compress.

   d) Deal Terms Vary From 10¢ to 36¢/mcf and 3% to 8% Fuel

2) Lower Pressure Pipeline Markets

   a) Enerfin, Duke, Ozark

   b) Deal Terms Generally % of Proceeds

      Low Side – 65% to 70%
      High Side – 80% to 85%

   They Lay The Gathering Line to You

   Percentage depends on how close to their line, your volume and quality of gas.

INCREASED WELL COST

Well costs have increased in some categories dramatically due to increased demand for the vendor's services and increased fuel and labor costs.

	Then (1)	Now (2)
Surface Damages	$1,000	$2,500
Right-of-Way	$10 to $15/rod	$20 to $35/rod
Surveyors	$ 375	$ 400
Cement (1,000' Well)	$3,100	$4,941
Open Hole Logs	$ 990	$1,450
Drilling	$5 to $6/ft.	$8 to $10 /ft.
Drilling Daywork	$ 200/hr.	$ 300/hr.
Workover Rigs:		
Pole	$ 90/hr.	$ 125/hr.
Double	$ 115/hr.	$ 140/hr.
Tubing Tongs	$ 75/day	$ 125/day

Plus all the add on Additional Costs: Acid Swabbing, Travel Time, Fuel Surcharge, etc.

(1) 1st six months of year 2000

(2) February 2001

revised October 2001

Coalbed Methane
(Selected References for Oklahoma)
by Brian J. Cardott

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